

- [1] P. Thounthong, B. Davat, and S. Raël, "Drive friendly," *IEEE Power Energy Mag.*, vol. 6, no. 1, pp. 69–76, Jan./Feb. 2008.
- [2] M. W. Ellis, M. R. Von Spakovsky, and D. J. Nelson, "Fuel cell systems: Efficient, flexible energy conversion for the 21st century," *Proc. IEEE*, vol. 89, no. 12, pp. 1808–1818, Dec. 2001.
- [3] W. Friede, S. Raël, and B. Davat, "Mathematical model and characterization of the transient behavior of a PEM fuel cell," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1234–1241, Sept. 2004.
- [4] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel cell high power applications," *IEEE Ind. Electron. Mag.*, vol. 3, no. 1, pp. 32–46, Mar. 2009.
- [5] M. Hinaje, I. Sadli, J.-P. Martin, P. Thounthong, S. Raël, and B. Davat, "Online humidification diagnosis of a PEMFC using a static dc-dc converter," *Int. J. Hydrogen Energy*, vol. 34, no. 6, pp. 2718–2723, Mar. 2009.
- [6] I. Sadli, P. Thounthong, J.-P. Martin, S. Raël, and B. Davat, "Behaviour of a PEMFC supplying a low voltage static converter," *J. Power Sources*, vol. 156, no. 1, pp. 119–125, May 2006.
- [7] The IEA Photovoltaic Power Systems Programme, "Trends in photovoltaic applications," Survey report 2008.
- [8] R. M. Nelms, D. R. Cahela, and B. J. Tatarchuk, "Modeling double-layer capacitor behavior using ladder circuits," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 39, no. 2, pp. 430–438, Apr. 2003.
- [9] P. Thounthong and S. Raël, "The Benefits of hybridization," *IEEE Ind. Electron. Mag.*, vol. 3, no. 3, pp. 25–37, Sept. 2009.
- [10] P. Thounthong, S. Raël, and B. Davat, "Analysis of supercapacitor as second source based on fuel cell power generation," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 247–255, Mar. 2009.
- [11] J. R. Miller and D. A. Evans, "Performance characteristics of high reliability double layer capacitor components," in *Proc. 35th IEEE Int. Power Sources Symp.*, Cherry Hill, NJ, Jan. 22–25, 1992, pp. 302–305.
- [12] Rajashekara, J. Grieve, and D. Daggett, "Hybrid fuel cell power in aircraft," *IEEE Ind. Appl. Mag.*, vol. 14, no. 4, pp. 54–60, July-Aug. 2008.
- [13] D. Maksimovic, A. M. Stankovic, V. J. Thsottuvelil, and G. C. Verghese, "Modeling and simulation of power electronic converters," *Proc. IEEE*, vol. 89, no. 6, pp. 898–942, Jun. 2001.
- [14] E. V. Dijk, H. J. N. Spruijt, D. M. O'Sullivan, and J. B. Klaassens, "PWM-switch modeling of DC–DC converters," *IEEE Trans. Power Electron.*, vol. 10, no. 6, pp. 659–665, Nov. 1995.
- [15] D. J. Perreault and J. G. Kassakian, "Distributed Interleaving of Paralleled Power Converters," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 44, no. 8, pp. 728–734, Aug. 1997.

- [16] M. Veerachary, T. Senjyu, and K. Uezato, "Signal flow graph nonlinear modelling of interleaved Converters," *IEE Proc. Electr. Power Appl.*, vol. 148, no. 5, pp. 410–418, Sep. 2001.
- [17] H. B. Shin, J. G. Park, S. K. Chung, H. W. Lee, and T.A. Lipo, "Generalised steady-state analysis of multiphase interleaved boost converter with coupled inductors," *IEE Proc. Electr. Power Appl.*, vol. 152, no. 3, pp. 584–594, May 2005.
- [18] M. Baumann, and J. W. Kolar, "Parallel connection of two three-phase three-switch buck-type unity-power-factor rectifier systems with DC-link current balancing," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3042–3053, Dec. 2007.
- [19] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle," *J. Power Sources*, vol. 158, no. 1, pp. 806–814, Jul. 2006.
- [20] M. Fliess, J. Lévine, Ph. Martin, and P. Rouchon, "Flatness and defect of nonlinear systems: Introductory theory and examples," *Int. J. Contr.*, vol. 61, no. 6, pp. 1327–1361, 1995.
- [21] M. Fliess, J. Lévine, P. Martin, and P. Rouchon, "A Lie–Bäcklund approach to equivalence and flatness of nonlinear systems," *IEEE Trans. Autom. Control*, vol. 44, no. 5, pp. 922–937, May 1999.
- [22] V. Morio, F. Cazaurang, and P. Vernis, "Flatness-based hypersonic reentry guidance of a lifting-body vehicle," *Control Engineering Practice*, vol. 17, no. 5, pp. 588–596, May 2009.
- [23] P. Thounthong and B. Davat, "Study of a multiphase interleaved step-up converter for fuel cell high power applications," *Energy Convers. Manage.*, vol. 51, no. 1, pp. 826–832, April 2010.
- [24] P. Thounthong, V. Chunkag, P. Sethakul, S. Sikkabut, S. Pierfederici, and B. Davat, "Energy management of fuel cell/solar cell/supercapacitor hybrid power source," *J. Power Sources*, 2010 (in press).
- [25] C. P. Mudannayake and M. F. Rahman, "Future automotive 42-V power net application," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 14–25, July–Aug. 2009.
- [26] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell and supercapacitors association for a distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3225–3233, Dec. 2007.
- [27] P. Thounthong, S. Raël, and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," *J. Power Sources*, no. 193, no. 1, pp. 376–385, August 2009.
- [28] E. Song, A. F. Lynch, and V. Dinavahi, "Experimental validation of nonlinear control for a voltage source converter," *IEEE Trans. Control System Technology*, vol. 17, no. 5, pp. 1135–1144, Sept. 2009.
- [29] A. Gensior, H. Sira-Ramirez, J. Rudolph, H. Guldner, "On some nonlinear current controllers for three-phase boost rectifiers," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 360–370, Feb. 2009.
- [30] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat, and M. Hinaje, "Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3892–3904, Oct. 2009.

- [31] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel starvation: Analysis of a PEM fuel cell system," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 52–59, Jul./Aug. 2009.
- [32] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 148–155, Jan. 2008.



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- 1.1 **P. Thounthong**, V. Chunkag, P. Sethakul, B. Davat, and M. Hinaje, "Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3892-3904, Oct. 2009. (2009 Impact Factor: 1.488) (ดูเอกสารแนบ)
- 1.2 **P. Thounthong**, V. Chunkag, P. Sethakul, S. Sikkabut, S. Pierfederici, and B. Davat, "Energy management of fuel cell/solar cell/supercapacitor hybrid power source," *J. Power Sources*, 2010 (in press). (2009 Impact Factor: 3.792) (ดูเอกสารแนบ)
- 1.3 **P. Thounthong**, B. Davat, S. Raël, and P. Sethakul, "Fuel cell high power applications," *IEEE Ind. Electron. Mag.*, vol. 3, no. 1, pp. 32-46, Mar. 2009. (2009 Impact Factor: 1.750) (ดูเอกสารแนบ)
- 1.4 **P. Thounthong**, B. Davat, S. Raël, and P. Sethakul, "Fuel starvation: Analysis of a PEM fuel cell system," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 52-59, Jul./Aug. 2009. (2009 Impact Factor: 0.727) (ดูเอกสารแนบ)
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- 1.8 **P. Thounthong**, S. Pierfederici, J.-P. Martin, M. Hinaje, and B. Davat, "Modeling and control of fuel cell/supercapacitor hybrid source based on differential flatness control," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 2700-2710, July 2010. (2009 Impact Factor: 1.488) (ดูเอกสารแนบ)
- 1.9 **P. Thounthong**, S. Pierfederici, and B. Davat, "Analysis of differential flatness-based control for a fuel cell hybrid power source," *IEEE Trans. Energy Convers.*, 2010 (in press). (2009 Impact Factor: 2.635) (ดูเอกสารแนบ)

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- 3.2 **P. Thounthong**, V. Chunkag, P. Sethakul, and B. Davat, "High-gain high-power converter for fuel cell applications," in *Proceeding of the Eleventh Grove Fuel Cell Symposium*, Queen Elizabeth II Conference Centre, Westminster, London, United Kingdom, 22-24 September 2009. Organized by Elsevier Publisher.
- 3.3 **P. Thounthong**, P. Sethakul, S. Raël, and B. Davat, "Performance Evaluation of Fuel Cell/Battery/Supercapacitor Hybrid Power Source for Vehicle Applications," in *Proceeding of the 2009 IEEE Industry Applications Society Annual Meeting (IAS-2009)*, Houston, Texas, USA, 4-8 October 2009. pp. 1-8 (CD-ROM).
- 3.4 **P. Thounthong**, N. Poonnoi, P. Sethakul, and B. Davat, "Performance Evaluation of Modified 4-phase Interleaved Fuel Cell Converter for High-Gain High-Power Applications," in *Proceeding of the 2009 IEEE Industry Applications Society Annual Meeting (IAS-2009)*, Houston, Texas, USA, 4-8 October 2009. pp. 1-8 (CD-ROM).
- 3.5 **P. Thounthong**, P. Sethakul, S. Raël, and B. Davat, "Fuel Cell Current Ripple Mitigation by Interleaved Technique for High Power Applications," in *Proceeding of the 2009 IEEE Industry Applications Society Annual Meeting (IAS-2009)*, Houston, Texas, USA, 4-8 October 2009. pp. 1-8 (CD-ROM).
- 3.6 **P. Thounthong**, S. Sikkabut, P. Sethakul, and B. Davat, "Control Algorithm of Renewable Energy Power Plant Supplied by Fuel Cell/Solar Cell/Supercapacitor Power Source," in *Proceeding of the 2010 International Power Electronics Conference (IPEC-Sapporo, ECCE ASIA)*, Sapporo, Hokkaido, Japan, USA, 21-24 June 2010, pp. 1155-1162, Organized by The Industry Applications Society of the Institute of Electrical Engineers of Japan (IEEJ) and IEEE.
- 3.7 **P. Thounthong**, S. Sikkabut, P. Sethakul, S. Pierfederici, and B. Davat, "Fuel Cell Power Regulation Based-on Differential Flatness Theory for High-Power Converter Applications," in *Proceeding of the 2010 IEEE-XIX International Conference on Electrical Machines (ICEM2010)*, Rome, Italy, 6-10 September 2010.
- 3.8 **P. Thounthong**, S. Pierfederici, and B. Davat, "Performance Evaluation of Differential Flatness Based-Control of Fuel Cell/Supercapacitor Hybrid Power Source," in *Proceeding of the 2010 IEEE-XIX International Conference on Electrical Machines (ICEM2010)*, Rome, Italy, 6-10 September 2010.
- 3.9 **P. Thounthong**, P. Mungporn, and B. Davat, "A Nonlinear Control Approach to the Energy Management of Solar Power Plant with Supercapacitor for Grid-Independent Applications," in *Proceeding of the 2010 IEEE-XIX International Conference on Electrical Machines (ICEM2010)*, Rome, Italy, 6-10 September 2010.

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# Comparative Study of Fuel-Cell Vehicle Hybridization with Battery or Supercapacitor Storage Device

Phatiphat Thounthong, *Member, IEEE*, Viboon Chunkag, Panarit Sethakul, Bernard Davat, *Member, IEEE*, and Melika Hinaje

**Abstract**—This paper studies the impact of fuel-cell (FC) performance and control strategies on the benefits of hybridization. One of the main weak points of the FC is slow dynamics dominated by a temperature and fuel-delivery system (pumps, valves, and, in some cases, a hydrogen reformer). As a result, fast load demand will cause a high voltage drop in a short time, which is recognized as a fuel-starvation phenomenon. Therefore, to employ an FC in vehicle applications, the electrical system must have at least an auxiliary power source to improve system performance when electrical loads demand high energy in a short time. The possibilities of using a supercapacitor or a battery bank as an auxiliary source with an FC main source are presented in detail. The studies of two hybrid power systems for vehicle applications, i.e., FC/battery and FC/supercapacitor hybrid power sources, are explained. Experimental results with small-scale devices (a polymer electrolyte membrane FC of 500 W, 40 A, and 13 V; a lead-acid battery module of 33 Ah and 48 V; and a supercapacitor module of 292 F, 500 A, and 30 V) in a laboratory authenticate that energy-storage devices can assist the FC to meet the vehicle power demand and help achieve better performance, as well as to substantiate the excellent control schemes during motor-drive cycles.

**Index Terms**—Battery, converters, current control, electric vehicles, fuel cells (FCs), power supplies, supercapacitor, voltage regulation.

## I. INTRODUCTION

FUEL CELLS (FCs) are able to generate electrical power with high efficiency, low operation noise, and no emissions

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from hydrogen gas and air. Byproducts are exhaust gases, water, and waste heat. The supplied electrical power can be used in vehicles for propulsion as well as for the operation of electrically powered accessories. Polymer electrolyte membrane (or proton exchange membrane) FCs (PEMFCs) utilize a solid polymer electrolyte membrane, operate at lower temperature, and are considered by many to be the most suitable for vehicle applications (such as cars, buses, tramways, trains, or aircraft) [1], [2].

Although recent literature portrays FCs as a newly emerging energy source, the technology was actually invented in the 19th century. In 1839, Sir William Grove, a Welsh judge and scientist, assembled the first FC. Since then, FCs have been primarily used in research settings. The National Aeronautics and Space Administration selected PEMFCs for the space program in the 1960s, rejecting both nuclear power, which had a higher safety risk, and solar power, which had a higher cost [1]. FCs provided power for the Gemini and Apollo missions and, at present, provide water and electricity to the space shuttle. Despite their high-profile use in the space program, the commercialization of FC technology was not explored until the early 1980s.

Many factors have limited the marketable development of FCs, including manufacturing cost, fuel generation and distribution, and system complexity. The high manufacturing cost is caused by a number of factors: expensive raw materials used as catalysts, expensive membrane materials, and expensive fabrication processes for collector plates.

In addition to manufacturing cost, fuel generation and distribution have also prevented widespread commercialization. Most FCs consume pure hydrogen or hydrogen-rich gas as the primary fuel. So far, experimental results and real-world applications of PEMFCs revealed that they perform best on pure hydrogen (H<sub>2</sub>) as anode input gas. However, for many applications, particularly mobile, due to a lack of availability of refueling infrastructure and impractical storage techniques, pure hydrogen is not yet a viable option. Pure hydrogen as an anode gas source for PEMFCs, at this time, has a number of formidable limitations. One of the major limitations is onboard hydrogen storage. As a viable alternative for carrying pure hydrogen, onboard hydrogen generation by reforming hydrocarbons such as natural gas, gasoline, or alcohol fuels would be an obvious choice. However, gas produced from a reformer contains about 70%–75% hydrogen, 20%–25% carbon dioxide (CO<sub>2</sub> poisoning), and 10–100 ppm carbon monoxide

(CO poisoning) [3]; furthermore, these reformers are large and expensive, and they operate at high temperatures.

Since most advanced vehicles like FC electric vehicles have one energy storage (buffer) device as part of the propulsion system, it is possible and necessary to apply advanced control technologies to significantly optimize the vehicle's fuel economy, emissions, and/or drivability [4], [5].

Nonetheless, the recent studies of Corrêa *et al.* [6], who worked with a 0.5-kW PEMFC (BCS Technology Company) and a 0.5-kW PEMFC (Avista Company), Thounthong *et al.* [5], [7], who worked with a 0.5-kW PEMFC [Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW) Company, Germany] and a 1.2-kW Nexa PEMFC (Ballard Power System Company, Canada), Adzakpa *et al.* [8], who worked with a 0.6-kW PEMFC (H Power Company), Wang *et al.* [9], who worked with a 0.5-kW PEMFC (Avista Company), and Gaynor *et al.* [10], who worked with a 350-kW Solid Oxide FC, have demonstrated the fact that the FC time constants are dominated by a temperature and fuel-delivery system (pumps, valves, and, in some cases, a hydrogen reformer). As a result, fast energy demand will cause a high voltage drop in a short time, which is recognized as a fuel-starvation phenomenon [11].

When starved from fuel or oxygen, the FC performance degrades, and the cell voltage drops. This condition of operation is evidently hazardous for the FC stack [11], [12]. Fuel starvation can result in generation of hydrogen in the cathode or oxygen in the anode. For instance, in the event of hydrogen starvation, the cell current cannot be maintained, causing a high anode potential. Therefore, the water, which is present at the anode, may split into hydrogen and oxygen, producing oxygen in the anode. In the same way, during oxygen starvation, the reaction at the cathode will produce hydrogen. The presence of oxygen at the anode and hydrogen at the cathode will lead to the reversal of the cell potential, which is a negative potential difference between the anode and the cathode. Cell reversal accelerates the corrosion of carbon components such as backing layers with ensuing electrocatalyst corrosion and eventually leads to damaged components. During hydrogen starvation, oxygen at the anode can react with the carbon present in the gas diffusion and backing layers to form carbon dioxide (CO<sub>2</sub> poisoning).

Thus, to utilize an FC in dynamic applications, its current or power slope must be limited to circumvent the fuel-starvation problem, e.g., 4 A · s<sup>-1</sup> for a 0.5-kW 12.5-V PEMFC [13] and 5, 10, and 50 A · s<sup>-1</sup> for a 20-kW 48-V PEMFC [14]. As a result, the vehicle electrical system must have at least an auxiliary power source (an energy storage device), such as a battery, supercapacitor, or flywheel, to improve the system performance when electrical loads at a dc bus demand high power in a short time (e.g., vehicle acceleration and deceleration) [15], [16]. Therefore, an FC vehicle can benefit from being hybridized with an energy-storage device [17]–[19], which assumes some of the roles that the FC would normally handle.

This paper deals with the conception and the achievement of a hybrid power source that is supplied by a PEMFC as the main energy source and a battery or a supercapacitor as an auxiliary power source, particularly for future vehicle

applications. Its interest is focused on control algorithms. It enables the management of transient power demand, power peaks, and regenerative braking with regard to FC, battery, and supercapacitor constraints. The general structures of the studied systems, the control principles of the hybrid sources, the realization of the experimental bench, and the experimental validation will be presented in the following sections.

## II. BATTERY VERSUS SUPERCAPACITOR AS AN ENERGY-STORAGE DEVICE

Currently, the battery is still the most extensive energy-storage device for providing and deliver electricity. There are many kinds of battery technology, such as lead-acid, NiCd, NiMH, or Li-ion. For a lead-acid cell, the terminal voltage of battery  $V_b$  and the internal resistance  $R_b$  are strong functions of the state of charge (SOC). The battery actual voltage curve is not constant. This is because the internal resistance is almost linear during the discharge, but the losses are substantially below 25% SOC due to the increase in the internal resistance. Therefore, the battery SOC estimation is defined here again as [20], [21]

$$\text{SOC}(t) = \frac{1}{Q_{\text{Bat}}} \int_{t_0}^t i_{\text{Bat}}(t) \cdot dt + \text{SOC}_0(t_0) \quad (1)$$

where  $\text{SOC}_0$  is the known battery SOC (in percentage) at time  $t_0$ ,  $Q_{\text{Bat}}$  is the rated capacity (in ampere-hours), and  $i_{\text{Bat}}(t)$  is the charging battery current (in amperes).

Supercapacitors (or ultracapacitors) are an emerging technology in the field of energy storage systems. Current breakthroughs in material design and fabrication methods that are aimed at maximizing rated capacitance have provided tremendous increases in the energy-storage capabilities of supercapacitors [22], [23]. The terminal voltage of supercapacitors is limited, however, due to the dissociation of the electrolyte. This limits the maximum voltage to 2.5–3 V.

When comparing the power characteristics of supercapacitors and batteries, the comparisons should be made for the same charge/discharge efficiency. The relative performance of supercapacitors and power batteries can be directly assessed from the pulse power tests since both types of devices are capable of high-power pulses, although batteries are not intended to be charged/discharged for long periods at these high power levels. The pulse testing of a battery is usually done at a specified partial SOC, as only a small fraction of the energy stored in the battery is used in the cycle tests. Of particular interest in the pulse tests is the round-trip efficiency of the devices. This is determined from the ratio of the energy out of the devices to the energy into the devices during the test cycle. This efficiency primarily depends on the internal equivalent series resistance (ESR) of the device. For supercapacitors, their charge/discharge efficiency is high, and the energy lost to heat during each cycle is relatively small and readily removed. The energy lost to heat in batteries is a much larger amount, making heat removal more crucial and its extraction costs much higher. This is to say that the cycle efficiency of batteries is around 80%, and the cycle efficiency of supercapacitors is around 95% [24], [25]. For a

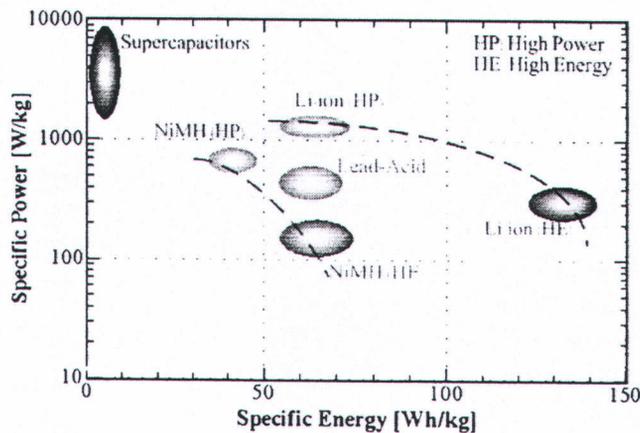


Fig. 1. Specific power versus specific energy of modern storage devices: supercapacitor, lead-acid, NiMH, and Li-ion battery technology. Note that the supercapacitors, NiMH, and Li-ion batteries are based on SAFT Company (France) technology.

corresponding high-efficiency discharge, batteries would have a much lower power capability.

Furthermore, the main drawback of batteries is a slow charging time, limited by a charging current [25], [26]; in contrast, supercapacitors may be charged over a short time, depending on a high charging current (power) that is available from the main source. Capacitor voltage  $v_C$  can then be found using the following classical equation:

$$v_C(t) = \frac{1}{C} \int_{t_0}^t i_C(t) \cdot dt + v_C(t_0) \quad (2)$$

where  $i_C(t)$  is the charging capacitor current.

Moreover, Fig. 1 compares the advanced technologies of batteries and supercapacitors in terms of specific power and energy. Although it is true that a battery has the largest energy density (i.e., more energy is stored per weight than other technologies), it is important to consider the availability of that energy. This is the traditional advantage of capacitors. With a time constant of less than 0.1 s, energy can be taken from a capacitor at a very high rate [27], [28]. On the contrary, a battery of the same size will not be able to supply the necessary energy in the same time period. Unlike batteries, more advantageous for the case of supercapacitors is the fact that they can withstand a very large number of charge/discharge cycles without degradation (or virtually infinite cycles) [24], [25].

### III. FC/BATTERY AND FC/SUPERCAPACITOR HYBRID POWER SOURCES

#### A. Structure of the Hybrid Power Sources

Different power converter topologies can be used for the power electronic interface between the FC and the utility dc bus. For the dc link voltage level, it depends on its applications. Basically, low-voltage high-current structures are needed because of FC electrical characteristics. A classical boost converter is often selected as an "FC converter" [29]–[31] because it can be operated in the current control mode in a continuous

condition mode. Then, one does not need a blocking diode and a passive filter between an FC and a converter. Based on the load conditions, the boost converter can be commanded to draw a specific amount of current from the FC with a ripple that is well defined by the frequency, the size of the inductor, and the duty ratio. However, a classical boost converter will be limited when the power increases or for higher step-up ratios.

In many applications, the use of an isolation transformer can provide an increased output/input voltage conversion ratio, as required, and full-bridge topologies can be used [7]. However, there are applications where transformer-less energy converter systems could potentially offer significant advantages, including simplicity, cost, and converter size reduction, particularly in high-power applications. That way, the use of paralleling power converters with an interleaved technique may offer some better performances [7].

One may summarize here again that the constraints to operate an FC are as follows.

- 1) The FC power or current must be kept within an interval (a rated value, a minimum value, or zero).
- 2) The FC current must be controlled as a unidirectional current.
- 3) The FC current slope must be limited to the maximum absolute value (e.g.,  $4 \text{ A} \cdot \text{s}^{-1}$  [13], [32]) to prevent an FC stack from the fuel starvation phenomenon.
- 4) The switching frequency of the FC current must be greater than 1.25 kHz and the FC ripple current must be lower than around 5% of the rated value to ensure minor impact to the FC conditions [7].

Proposed hybrid power sources are depicted in Figs. 2 and 3. The battery actual voltage curve is not constant. It is linear over most of its operating range. The battery voltage variation is at least 25%. Nonetheless, at the end of discharge, the battery voltage decreases very rapidly toward zero. This is because the internal resistance of a lead-acid battery is almost linear during discharge, but the losses are largely below 25% SOC due to the increase in the internal resistance of the battery. As depicted in Fig. 2, we propose the FC/battery hybrid source by directly connecting the battery module to a dc bus [33], [34]. For this reason, there is no battery converter in this structure to improve system efficiency and converter cost. Then, this system will be operated based on unregulated dc bus voltage, in which the dc bus voltage is equal to the battery voltage.

For the FC/supercapacitor hybrid source (see Fig. 3), a supercapacitor module is frequently connected to the dc bus by means of a classical two-quadrant (bidirectional) dc/dc converter [35]–[38]. Supercapacitor current  $i_{\text{SuperC}}$ , which flows across the storage device, can be positive or negative, allowing energy to be transferred in both directions.

#### B. Energy Management of the Hybrid Power Sources

When an FC operates, its fuel (hydrogen and oxygen) flows are controlled by an "FC controller," which receives current demand. This current demand is the FC current reference  $i_{\text{FCREF}}$  coming from the hybrid control algorithms detailed hereafter. The fuel flows must be adjusted to match the reactant delivery

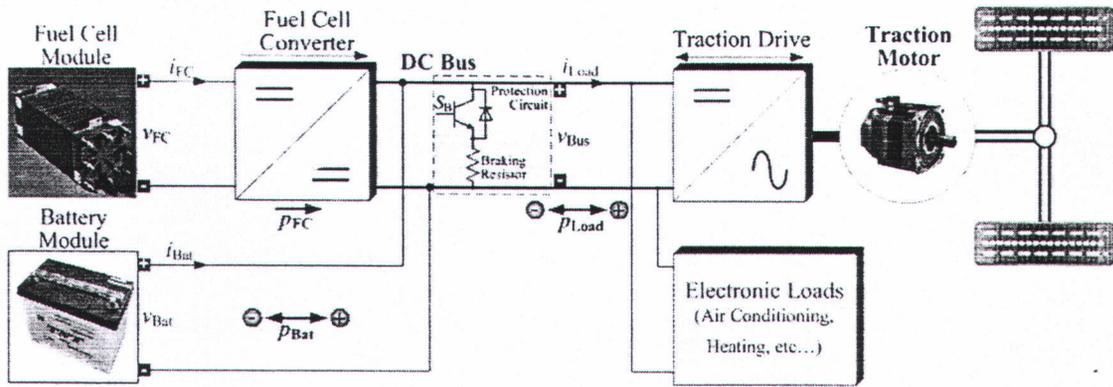


Fig. 2. Proposed structure of the FC/battery hybrid power source, where  $p_{FC} (= v_{FC} \times i_{FC})$ ,  $v_{FC}$ , and  $i_{FC}$  are the FC power, voltage, and current, respectively.  $p_{Bat} (= v_{Bat} \times i_{Bat})$ ,  $v_{Bat}$ , and  $i_{Bat}$  are the battery power, voltage, and current, respectively.  $p_{Load} (= v_{Bus} \times i_{Load})$ ,  $v_{Bus}$ , and  $i_{Load}$  are the load power, the dc bus voltage, and the load current, respectively. Note that it has been assumed that there are no losses in the FC converter, and here,  $v_{Bus}$  is  $v_{Bat}$ .

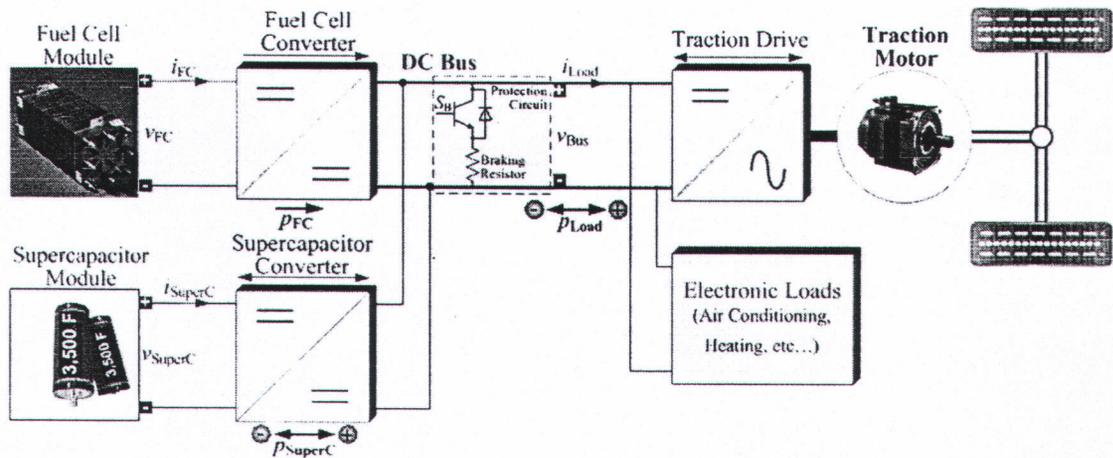


Fig. 3. Proposed structure of the FC/supercapacitor hybrid power source, where  $p_{FC} (= v_{FC} \times i_{FC})$ ,  $v_{FC}$ , and  $i_{FC}$  are the FC power, voltage, and current, respectively.  $p_{SuperC} (= v_{SuperC} \times i_{SuperC})$ ,  $v_{SuperC}$ , and  $i_{SuperC}$  are the supercapacitor power, voltage, and current, respectively.  $p_{Load} (= v_{Bus} \times i_{Load})$ ,  $v_{Bus}$ , and  $i_{Load}$  are the load power, the dc bus voltage, and the load current, respectively. Note that it has been assumed that there are no losses in the FC and supercapacitor converters.

rate to the usage rate by the FC controller [39]. For this reason, the inner FC current control loop is obligatory, and the hybrid control algorithms demand energy from the FC to the dc link by generating  $i_{FCREF}$  [1], which is synchronously sent to the FC system. One can take advantage of the safety and high dynamic characteristics of this loop as well. Note that the definitions of current direction are also illustrated in Figs. 2 and 3, and the dynamics of the current regulation loops are also supposed to be much faster than those of the outer control loops, which are detailed hereafter.

The energy management of hybrid power sources has already been studied recently, for example, by Jiang and Dougal [40], who worked on an unregulated voltage FC/battery hybrid source; by Ayad *et al.* [41], who studied the control of an unregulated voltage battery/supercapacitor hybrid source; and by Thounthong *et al.* [42], whose work concerned a regulated voltage FC/supercapacitor hybrid source. The problem of such a control strategy is well known: The definition of system states (state-machine-used) implies control algorithm permutations that may lead to a phenomenon of chattering when the system is operating near a border between two states. Of course, solutions

exist to avoid such a phenomenon—hard filtering, hysteric transition, and transition defined by a continuous function.

The control algorithm presented here is not based on the state definition; therefore, naturally, it does not present the problem of chattering near state borders. Its basic principle lies in using the storage device, which is the fastest energy source of the system, to supply the energy that is required to the load, as if this device were a standard power supply. Therefore, the FC, although obviously the main energy source of the system, functions as the source that supplies energy to storage devices to keep them charged.

1) *FC/Battery Hybrid Power Source*: One takes advantage of a battery bank, which is directly connected to a dc bus to supply transient energy demand and peak loads that are required during traction motor acceleration and deceleration, as if this device is a standard power supply [43]–[45]. The proposed control strategy is a cascade control structure composed of three loops, as portrayed in Fig. 4. The outer loop is the battery SOC control that links the battery SOC to the battery charging current reference  $i_{BatREF}$ . The middle loop controls the battery-charging current and links  $i_{BatREF}$  to the FC current

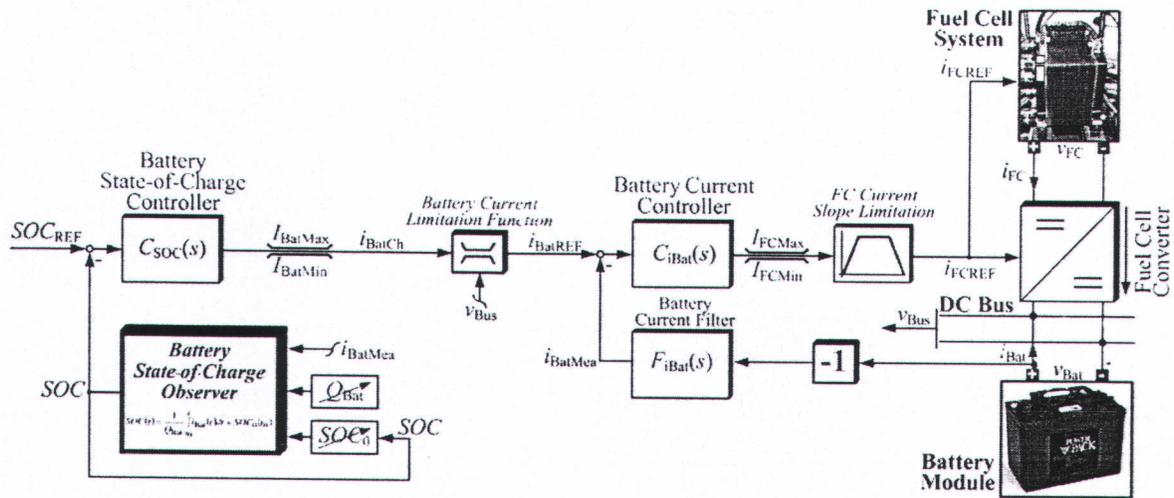


Fig. 4. Proposed energy management of the FC/battery hybrid power source.

reference  $i_{FCREF}$ . The inner loop is the FC current control, which is not presented in Fig. 4.

A simple method to charge the battery is with constant current (maximum charging current  $I_{BatMax}$  is set around  $Q_{Bat}/10$ ; for a modern Li-ion battery, it can be set at  $I_{BatMax} = Q_{Bat}$ ) when the SOC is far from the SOC reference  $SOC_{REF}$ , with reduced current when the SOC is near  $SOC_{REF}$ , or with no current when the SOC is equal to  $SOC_{REF}$ . For the battery SOC, it is estimated from (1), as depicted in "Battery State-of-Charge Observer" in Fig. 4.

More importantly, in vehicle applications, to replace aged batteries, battery monitoring is compulsory. In particular, the potential capacity  $Q_{Bat}$  is dependent on the depth of the discharge, the discharge rate, the cell temperature, the charging regime, the dwell time at low and high SOC, battery maintenance procedures, the current ripple, and the amount and frequency of overcharge [21].

It is beyond the scope of this paper to observe the potential capacity of the battery. It is assumed that  $Q_{Bat}$  is constant. Additionally, in a real system of applications,  $SOC_0$  can be retained in a storage device.

According to this SOC control algorithm, the "Battery State-of-Charge Controller" generates a battery-charging current  $i_{BatCh}$  for the battery current control loop. The battery current command  $i_{BatCh}$  must be limited within an interval [maximum charging current  $I_{BatMax}$ , maximum discharging current  $I_{BatMin}$ ].

To avoid overvoltage at the dc bus in case of an erroneous SOC estimation or high regenerative braking, the dc bus voltage (the battery voltage) must be monitored to limit the charging current. The "Battery Current Limitation Function" consists of limiting the battery current reference  $i_{BatREF}$  versus the dc bus voltage as

$$i_{BatREF}(t) = i_{BatCh}(t) \cdot \min \left( 1, \frac{V_{BusMax} - v_{Bus}(t)}{\Delta v_{Bus}} \right) \quad (3)$$

where  $V_{BusMax}$  is the defined maximum dc bus voltage, and  $\Delta v_{Bus}$  is the defined voltage band.

The battery-current control loop receives  $i_{BatREF}$  from an SOC regulation loop. The measured battery current must be reversed because the definition of the battery current is negative for the charging current. The battery current controller generates the FC current reference  $i_{FCREF}$ . It must be limited in level, within the interval maximum  $I_{FCMax}$  (corresponding to a rated current of the FC) and minimum  $I_{FCMin}$  (set to 0 A) and limited in slope to the maximum absolute value (in amperes per second), which enables the safe operation of the FC with respect to the constraints that are associated with the FC.

One may summarize that the control principle of the whole system is based on the battery SOC, whatever the load power is.

- If the SOC is lower than  $SOC_{REF}$ , the battery-charging current reference is a negative value, and an FC current is necessary to charge the battery.
- If the SOC is higher than  $SOC_{REF}$ , the battery-charging current reference is a positive value or equal to zero, and the FC current reference is reduced to zero.

As a consequence, a transient in the load modifies the FC current when the battery SOC becomes lower than  $SOC_{REF}$ . In any case, if the SOC is higher than  $SOC_{REF}$ , the FC current reference is equal to zero. For transient conditions, as FC current dynamics have been intentionally reduced, the battery supplies all load variations.

It must be noted here that, in this system, the PEMFC is the main source, and the battery module is the secondary source. The battery functions to compensate the FC dynamic performance to avoid the FC starvation problem, supply the overenergy demand, and absorb the regenerative braking energy. There are two possibilities to connect a battery module with a dc bus. First, a battery bank is directly connected to the dc bus as proposed in our system. Second, a battery bank may be connected to the dc bus by a bidirectional converter, but it will increase system losses and cost. Nevertheless, the battery will be cycled whenever there is a load. Because, as mentioned earlier, the battery lifetime is usually limited by the number of cycles, its longevity might suffer. There are no solutions to improve the battery lifetime in the FC/battery hybrid source.

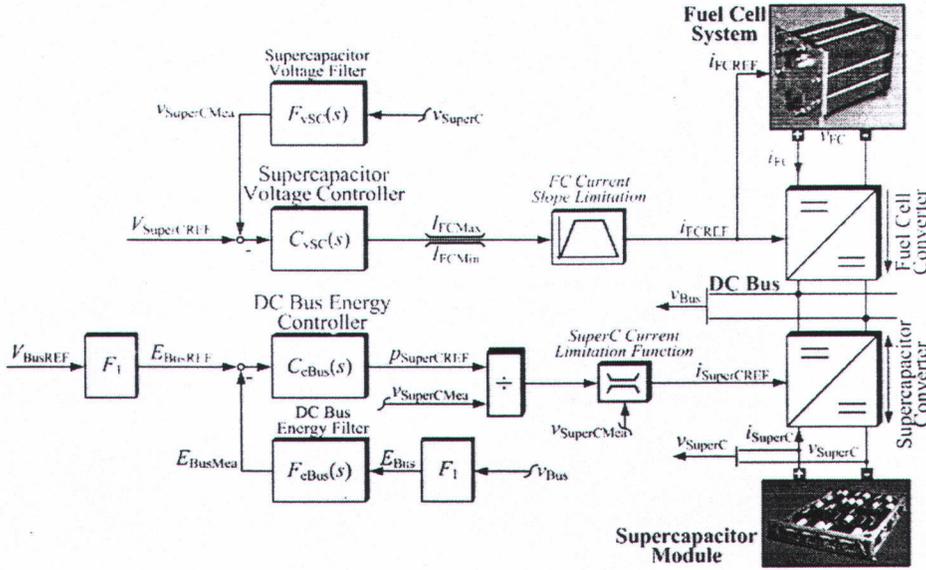


Fig. 5. Proposed energy management of the FC/supercapacitor hybrid power source.

even if a battery bank is directly connected to the dc bus or to the dc bus by a bidirectional converter. The battery will be always cycled whenever there is a load because the FC power dynamics are compensated by the battery power. To improve the battery lifetime, an FC/battery/supercapacitor hybrid source is proposed. We want the supercapacitor to supply or to absorb the load transient power and not the battery. Nonetheless, this system is under study [18].

2) *FC/Supercapacitor Hybrid Power Source*: To manage energy change in the system, its basic principle lies in using the supercapacitor, which is the fastest energy source of the system, to supply the energy that is required to achieve the dc bus voltage regulation, as if this device were a standard power supply. Therefore, the FC, although obviously the main energy source of the system, is equivalent to a load working only in regenerative braking and may be seen as a device that supplies energy to supercapacitors to keep them charged [44].

Consequently, the supercapacitor converter is driven to realize a classical dc bus voltage regulation, and the FC converter is driven to maintain the supercapacitor module at a given SOC. Therefore, the dynamics of the current regulation loops are also supposed to be much faster than those of the outer control loops. Thus, the currents  $i_{\text{SuperC}}$  and  $i_{\text{FC}}$  are considered to perfectly follow their references  $i_{\text{SuperCREF}}$  and  $i_{\text{FCREF}}$ , respectively. The supercapacitor and FC current control loops are supplied by two reference signals, i.e.,  $i_{\text{SuperCREF}}$  and  $i_{\text{FCREF}}$ , which are generated by the dc bus voltage regulation loop and the supercapacitor voltage regulation loop, as shown in Fig. 5.

For the dc bus voltage control loop, it uses the dc bus capacitive energy  $E_{\text{Bus}}$  as the state variable and the supercapacitor delivered power  $p_{\text{SuperCREF}}$  as the command variable to obtain a natural linear transfer function for the system. If the losses in both the FC and supercapacitor converters are neglected, the dc link capacitive energy  $E_{\text{Bus}}$  is given versus supercapacitor

power  $p_{\text{SuperC}}$ , FC power  $p_{\text{FC}}$ , and load power  $p_{\text{Load}}$  by the following differential equation:

$$\frac{dE_{\text{Bus}}(t)}{dt} = p_{\text{SuperC}}(t) + p_{\text{FC}}(t) - p_{\text{Load}}(t). \quad (4)$$

Function “ $F_1$ ” presented in Fig. 5 is a voltage-to-energy transformation, which is proportional for the total dc bus capacitance  $C_{\text{Bus}}$  to the square function

$$E_{\text{Bus}}(t) = \frac{1}{2} \cdot C_{\text{Bus}} \cdot v_{\text{Bus}}^2(t). \quad (5)$$

It enables the generation of both dc bus energy reference  $E_{\text{BusREF}}$  and dc bus energy measurement  $E_{\text{BusMea}}$  through dc bus voltage reference  $V_{\text{BusREF}}$  and dc bus voltage measurement  $v_{\text{Bus}}$ , respectively. The “DC Bus Energy Controller” generates a supercapacitor power reference  $p_{\text{SuperCREF}}$ . This signal is then divided by the measured supercapacitor voltage  $v_{\text{SuperCMea}}$  and limited to maintain the supercapacitor voltage within an interval  $[V_{\text{SuperCMin}}, V_{\text{SuperCMax}}]$ . The upper value of this interval corresponds to the rated voltage of the storage device, and the lower value, which is traditionally equal to  $V_{\text{SuperCMax}}/2$ , corresponds to a level under which the supercapacitor discharge becomes ineffective. This results in supercapacitor current reference  $i_{\text{SuperCREF}}$ .

The “SuperC Current Limitation Function” consists of limiting reference  $i_{\text{SuperCREF}}$  to the interval  $[I_{\text{SuperCMin}}, I_{\text{SuperCMax}}]$ , which is defined, versus measured supercapacitor voltage  $v_{\text{SuperCMea}}$ , as follows:

$$\left. \begin{aligned} I_{\text{SuperCMin}} &= -I_{\text{SuperCRated}} \\ &\quad \times \min \left( 1, \frac{V_{\text{SuperCMax}} - v_{\text{SuperCMea}}(t)}{\Delta v_{\text{SuperC}}} \right) \\ I_{\text{SuperCMax}} &= +I_{\text{SuperCRated}} \\ &\quad \times \min \left( 1, \frac{v_{\text{SuperCMea}}(t) - V_{\text{SuperCMin}}}{\Delta v_{\text{SuperC}}} \right) \end{aligned} \right\}. \quad (6)$$

$I_{\text{SuperCRated}}$  and  $\Delta v_{\text{SuperC}}$  are the regulation parameters.

For the supercapacitor voltage regulation loop, the “Supercapacitor Voltage Controller” generates an FC current reference  $i_{FCREF}$  limited in level and slope with respect to the constraints associated with the FC. The  $i_{FCREF}$  that drives the FC converter through the FC current loop is then kept within an interval  $[I_{FCMin}, I_{FCMax}]$ . The upper value of this interval corresponds to the rated current of the FC, and the lower value should be zero. Slope limitation to the maximum absolute value of some amperes per second enables safe operation of the FC, even during the transient power demand.

One may summarize that, using this form of control principle, the state of the supercapacitor module is naturally defined, through the dc bus voltage regulation, by the load power level, and by its SOC. In narrow steady-state conditions, we have the following.

- 1) If load power is negative, the dc link voltage regulation generates a negative supercapacitor current reference  $i_{SuperCREF}$ .
- 2) If load power is greater than the approximate FC rated power, the dc bus voltage regulation generates a positive supercapacitor current reference  $i_{SuperCREF}$ .
- 3) Otherwise, the state of the supercapacitor module depends on its SOC: the supercapacitor current will, therefore, be positive if  $v_{SuperC} > V_{SuperCREF}$  and negative if  $v_{SuperC} < V_{SuperCREF}$ .

In all cases, the FC state depends only on the supercapacitor voltage; the FC current will be strictly positive and less than  $I_{FCRated}$  if  $v_{SuperC} < V_{SuperCREF}$ . Otherwise, it will be zero. In transient conditions, as FC current dynamics have been intentionally reduced, the supercapacitor supplies load variations. In effect, the dc bus voltage regulation transforms a sudden increase in load power into a sudden increase in the supercapacitor current and, on the contrary, a sudden decrease in load power into a sudden decrease in the supercapacitor current.

3) *Conclusion of Proposed Energy-Management Algorithms:* The main important point in hybrid systems presented here is to balance the energy between the FC main source, the auxiliary source, and the load. The FC power (or current) dynamics have been intentionally reduced; the auxiliary source supplies all load variations.

Finally, Figs. 6 and 7 present simulation results during a high constant stepped load power. They show the load, auxiliary, and FC powers in per unit [p.u.]. In simulations, the FC minimum and maximum powers are set at 0 p.u. (corresponding to the FC minimum current) and 1.0 p.u. (corresponding to the FC maximum current), respectively. The power dynamics of the FC are set at  $0.6 \text{ p.u.} \cdot \text{s}^{-1}$ . As illustrated in Fig. 6, initially, the storage device is full of charge, and the load power is 0.2 p.u. As a result, the storage device power is zero, and the FC supplies 0.2 p.u. for the constant load power. At  $t = 1 \text{ s}$ , the constant load power steps to 3.0 p.u. One can observe the following.

- The auxiliary source supplies most of the transient power required.
- The FC power increases to the limited power 1.0 p.u. with a slope of  $0.6 \text{ p.u.} \cdot \text{s}^{-1}$ .

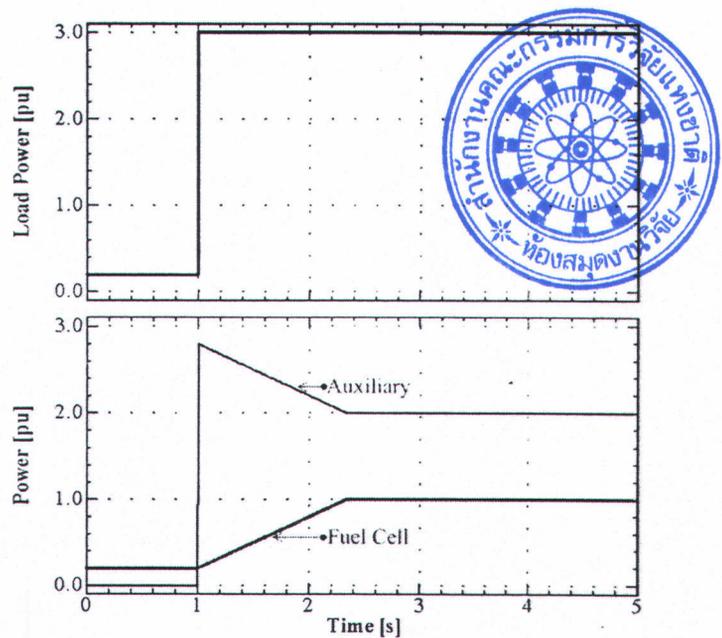


Fig. 6. Simulation result: hybrid source response during a high positive load step. Note that the power unit is per unit (p.u.).

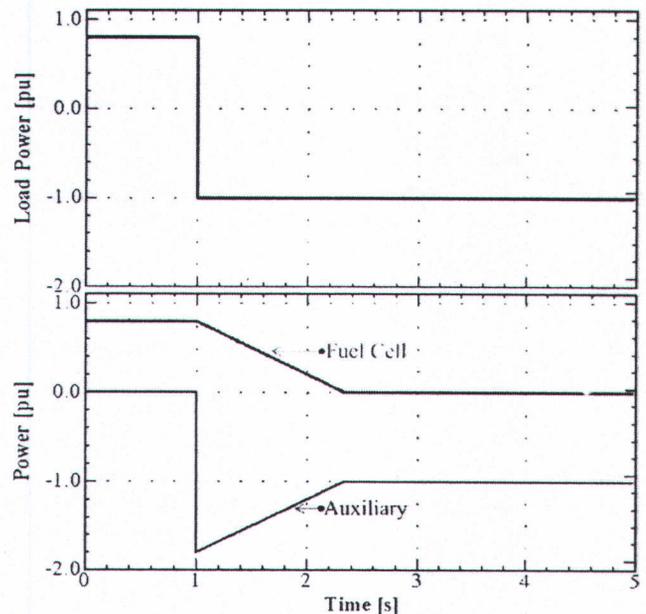


Fig. 7. Simulation result. Hybrid source response during a high negative load step (imitated regenerative braking).

- Synchronously, the auxiliary power, after a sharp increase (discharging), slowly decreases to a constant discharge of 2.0 p.u.

At a steady state, the constant load power of 3.0 p.u. is entirely supplied by the FC of 1.0 p.u. and the storage device of 2.0 p.u. (the discharging state).

As a final simulation illustrated in Fig. 7, initially, the auxiliary energy source is full of charge, and the load power is 0.8 p.u. As a result, the storage device power is zero, and the FC supplies 0.8 p.u. for the constant load power. At  $t = 1 \text{ s}$ , the

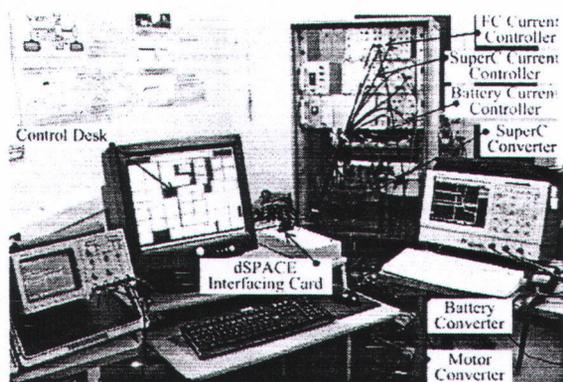


Fig. 8. Hybrid source test bench.

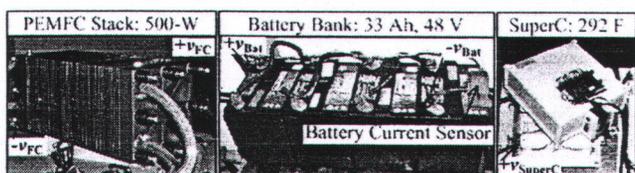


Fig. 9. PEMFC stack and storage devices.

constant load power steps to  $-1.0$  p.u. (imitated regenerative braking). One can see, again, the following.

- The auxiliary source absorbs most of the transient negative power.
- The FC power reduces to zero with a slope of  $0.6 \text{ p.u.} \cdot \text{s}^{-1}$  because the FC power source is a unidirectional power flow.
- Simultaneously, the auxiliary source, after a sharp decrease (charging), slowly increases to a constant charge at  $-1.0$  p.u.

#### IV. EXPERIMENTAL VERIFICATION

##### A. Test Bench Explanation

The small-scale test bench of the hybrid systems in our laboratory is presented in Fig. 8. As illustrated in Fig. 9, the PEMFC system (500 W, 40 A, 13 V) was achieved by the ZSW Company. It is composed of 23 cells of  $100 \text{ cm}^2$  in series. It is supplied using pure hydrogen from bottles under pressure and with clean and dry air from a compressor. The battery module is obtained by means of four aged lead-acid batteries [7.78 Ah (33 Ah at the nameplate), 12 V] connected in series. The supercapacitor module is obtained by means of 12 SAFT supercapacitors SC3500 (capacitance: 3500 F; rated voltage: 2.5 V; rated current: 500 A; low-frequency ESR:  $0.8 \text{ m}\Omega$ ) connected in series.

The FC converter is a classical boost converter and is selected to adapt the low dc voltage delivered by the FC, which is approximately 12.5 V at rated power, to the 42-V dc bus. Thus, the FC converter is composed of a high-frequency input inductor ( $72 \mu\text{H}$ ), an output filtering capacitor (Panasonic aluminum electrolytic capacitors:  $30\,000 \mu\text{F}$ ), a diode (Schottky diode STPS80H100TV: 100 V, 40 A), and a main power switch (power metal-oxide-semiconductor field-effect

transistor STE180NE10: 100 V, 180 A). The frequency of the pulsewidth modulation that drives the FC converter is 25 kHz.

The supercapacitor converter is a classical two-quadrant dc/dc converter (a bidirectional converter). Thus, the supercapacitor converter is composed of a high-frequency input inductor ( $54 \mu\text{H}$ ), an output filtering capacitor (Panasonic aluminum electrolytic capacitors: 330 mF), and two power switches (power insulated-gate bipolar transistors SKM200GB123D: 1200 V, 200 A). The supercapacitor current, which flows across the storage device, can either be positive or negative, allowing energy to be transferred in both directions. The converter is driven by means of complementary pulses, which are generated by a hysteresis comparator, and applied on the gates of the power switches.

In the case of the FC/battery hybrid power source test bench, the total dc bus capacitance is 360 mF (30 mF of the output capacitance of the FC converter and 330 mF of the output capacitance of the load converter). In the case of the FC/supercapacitor hybrid power source test bench, the total dc bus capacitance is 690 mF (30 mF of the output capacitance of the FC converter, 330 mF of the output capacitance of the load converter, and 330 mF of the output capacitance of the supercapacitor converter).

The dc bus is connected to only a traction motor drive (10 kW) coupled with a small-inertia flywheel. The supercapacitor and FC current control loops, on the other hand, have been realized by analog circuits to function at a high bandwidth. The proposed energy-control algorithms have been implemented in the real-time card dSPACE DS1104 through the mathematical environment of MATLAB-Simulink, with a sampling frequency of 25 kHz. The ControlDesk software enables changes in the parameters of the control loops. Two digital oscilloscopes (Tektronix Com.), as shown in Fig. 8, are used as data acquisition to store signal waveforms, which are presented hereafter.

The control parameters of the PEMFC are set as follows.

- $I_{FC\text{Max}} = 40 \text{ A}$  (rated FC current, corresponding to the rated FC power).
- $I_{FC\text{Min}} = 0 \text{ A}$  (minimum FC current, corresponding to the minimum FC power).
- The FC current absolute slope limitation is set to  $4 \text{ A} \cdot \text{s}^{-1}$  (corresponding to the FC power slope of around  $50 \text{ W} \cdot \text{s}^{-1}$ ). This value has been experimentally determined as the highest current slope of our FC system, where no fuel starvation occurs [13].

##### B. Test Results of the FC/Battery Hybrid Power Source

The controlled parameters of this system are set as follows:

- $\text{SOC}_{\text{REF}} = 100\%$  (equal to 7.78 Ah);
- $I_{\text{BatMax}} = +6 \text{ A}$  (the maximum battery charging current);
- $I_{\text{BatMin}} = -50 \text{ A}$  (the maximum battery discharging current);
- $V_{\text{BusMax}} = 61 \text{ V}$ ;
- $\Delta v_{\text{Bus}} = 2 \text{ V}$ .

Figs. 10 and 11 present waveforms that are obtained during the motor-drive cycle. They show the dc bus voltage (the battery voltage), the FC voltage, the load power, the battery power, the

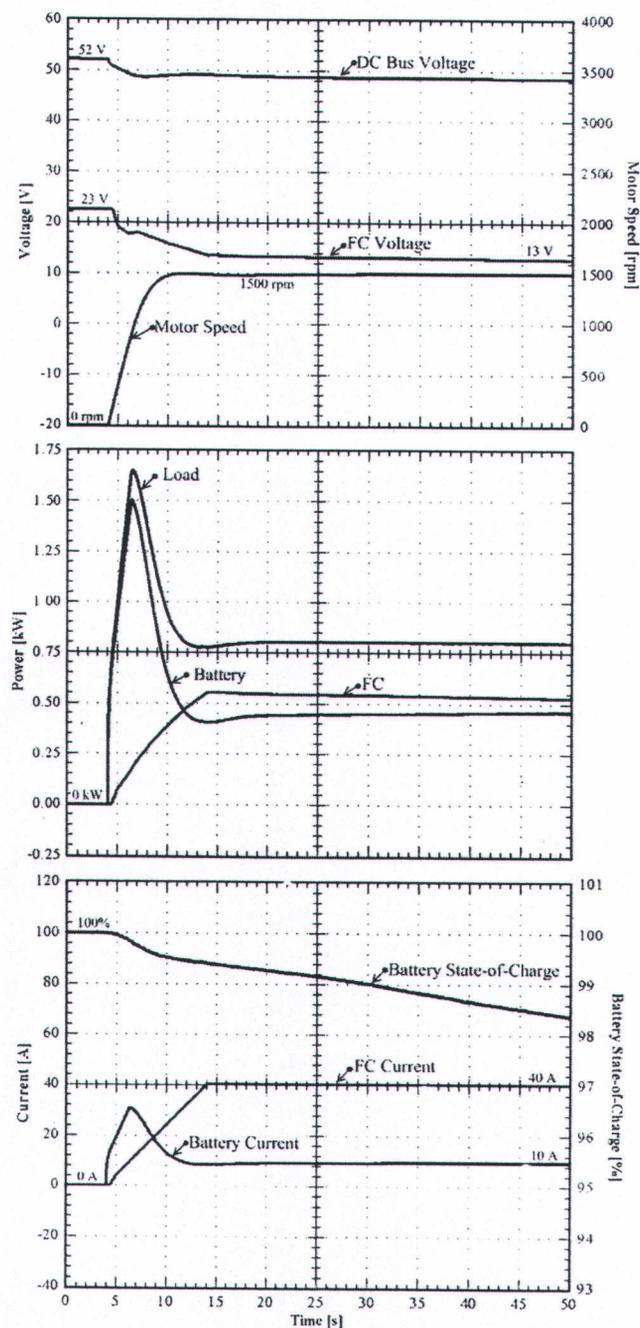


Fig. 10. FC/battery hybrid source response during motor starting to 1500 r/min.

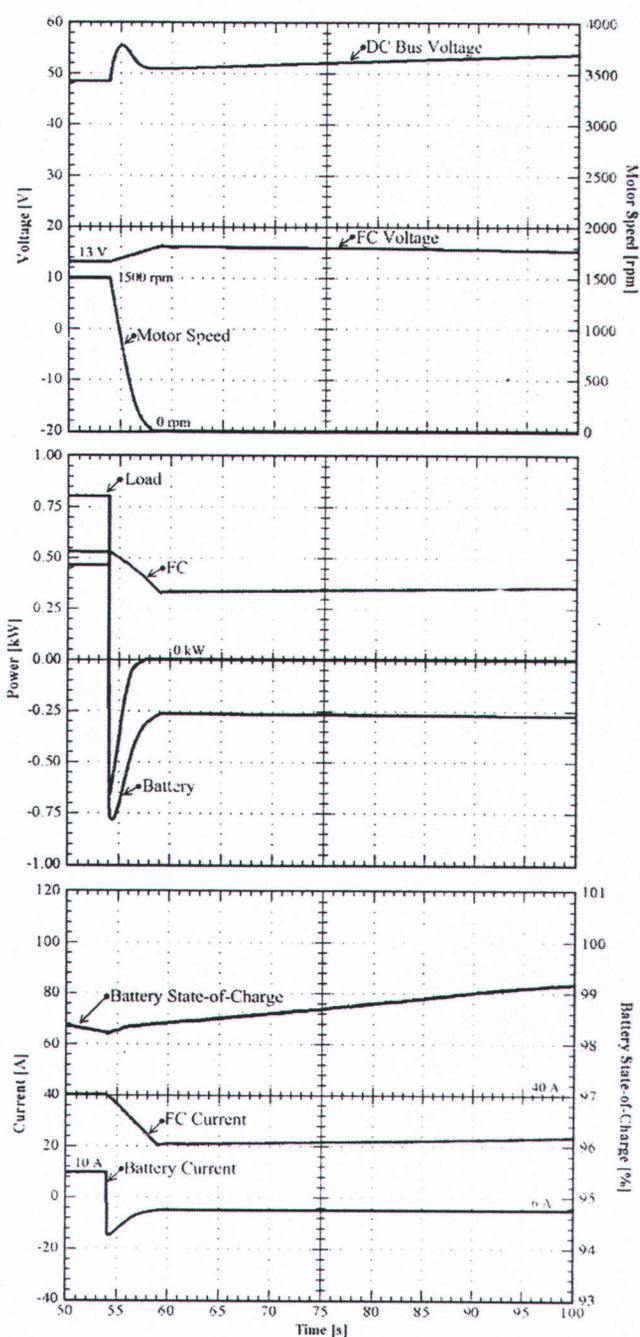


Fig. 11. FC/battery hybrid source response during motor braking from 1500 r/min.

FC power, the motor speed, the battery current, the FC current, and the battery SOC. The battery SOC is calculated from (1) by MATLAB-Simulink and is then sent through a digital-to-analog-converter card of dSPACE to an oscilloscope.

The initial state is zero for both the FC and battery powers and 100% for the battery SOC. At  $t = 4$  s, the motor reaches the final speed of 1500 r/min such that the final FC current is  $I_{FCRated}$ . One can observe the following.

- The battery supplies most of the power of 1600 W that is required during motor acceleration.

- The FC power increases with a limited slope up to a level of the rated power of 500 W.
- Concurrently, the battery power, after a sharp increase during motor acceleration, slowly decreases to a constant discharging power of 400 W.
- The steady-state load power at the constant speed of 1500 r/min is about 800 W, which is entirely supplied by the FC and the battery.

Therefore, this characteristic can be comparable with the simulation results in Figs. 6 and 7. After that, at  $t = 54$  s, the motor reduces speed and then stops. It can be scrutinized that

there are three phases. First, the battery recovers the power that is supplied to the dc link by the FC and the motor (known as the regenerative braking energy). Second, the battery recovers the reduced power that is supplied to the dc bus by only the FC. Third, the battery is charged at a constant current of 6 A by the FC. During the first and second phases, the FC power reduces from a rated power of 500 W with a constant slope of  $50 \text{ W} \cdot \text{s}^{-1}$ . In the third phase, the FC power is nearly constant at around 300 W to charge the battery. After that, both the FC and the battery power will reduce to zero when the SOC reaches  $\text{SOC}_{\text{REF}}$ .

*C. Test Results of the FC/Supercapacitor Hybrid Power Source*

The control parameters of this system are set as follows:

- $V_{\text{BusREF}} = 42 \text{ V}$  (a new standard dc bus voltage in the automotive electrical system called "PowerNet" [17]);
- $V_{\text{SuperCREF}} = 25 \text{ V}$ ;
- $V_{\text{SuperCMax}} = 30 \text{ V}$ ;
- $V_{\text{SuperCMin}} = 15 \text{ V}$ ;
- $I_{\text{SuperCRated}} = 200 \text{ A}$ ;
- $\Delta v_{\text{SuperC}} = 0.5 \text{ V}$ .

Figs. 12 and 13 present waveforms that are obtained during the motor-drive cycle. They show the dc bus voltage, the FC voltage, the load power, the supercapacitor power, the FC power, the motor speed, the supercapacitor current, the FC current, and the supercapacitor voltage (or the supercapacitor SOC).

The initial state is in no-load power, and the storage device is full of charge, i.e.,  $V_{\text{SuperC}} = 25 \text{ V}$ ; as a result, both the FC and supercapacitor powers are zero. At  $t = 20 \text{ s}$ , the motor speed accelerates to the final speed of 1000 r/min; synchronously, the final FC power increases with a limited slope of  $50 \text{ W} \cdot \text{s}^{-1}$  to a rated power of 500 W. Thus, the supercapacitor, which supplies most of the power that is required during motor acceleration, remains in a discharge state after the motor start because the steady-state load power (approximately 600 W) is greater than the FC rated power (500 W), and the peak load power is about 1000 W, which is about two times that of the FC rated power.

After that, at  $t = 50.5 \text{ s}$ , the motor speed decelerates and stops with a peak load power of about  $-500 \text{ W}$ . The supercapacitor is deeply charged, demonstrating the three phases. First, the supercapacitor recovers the energy that is supplied to the dc bus by the FC (500 W) and the traction motor. Second, the supercapacitor is charged only by the FC. Third, the supercapacitor is nearly fully charged, which then reduces the charging current. After that, both the FC and supercapacitor powers reduce to zero when  $V_{\text{SuperC}}$  reaches  $V_{\text{SuperCREF}}$  of 25 V.

Only small perturbations on the dc bus voltage waveform can be seen, which is of major importance when using supercapacitors to improve the dynamic performance of the whole system. These characteristics can be, again, comparable with the simulation results in Figs. 6 and 7.

The proposed energy-management algorithms of FC/battery and FC/supercapacitor hybrid sources are used to balance powers in the system with respect to dynamic constraints. During motor acceleration or deceleration (a high stepped load), as can

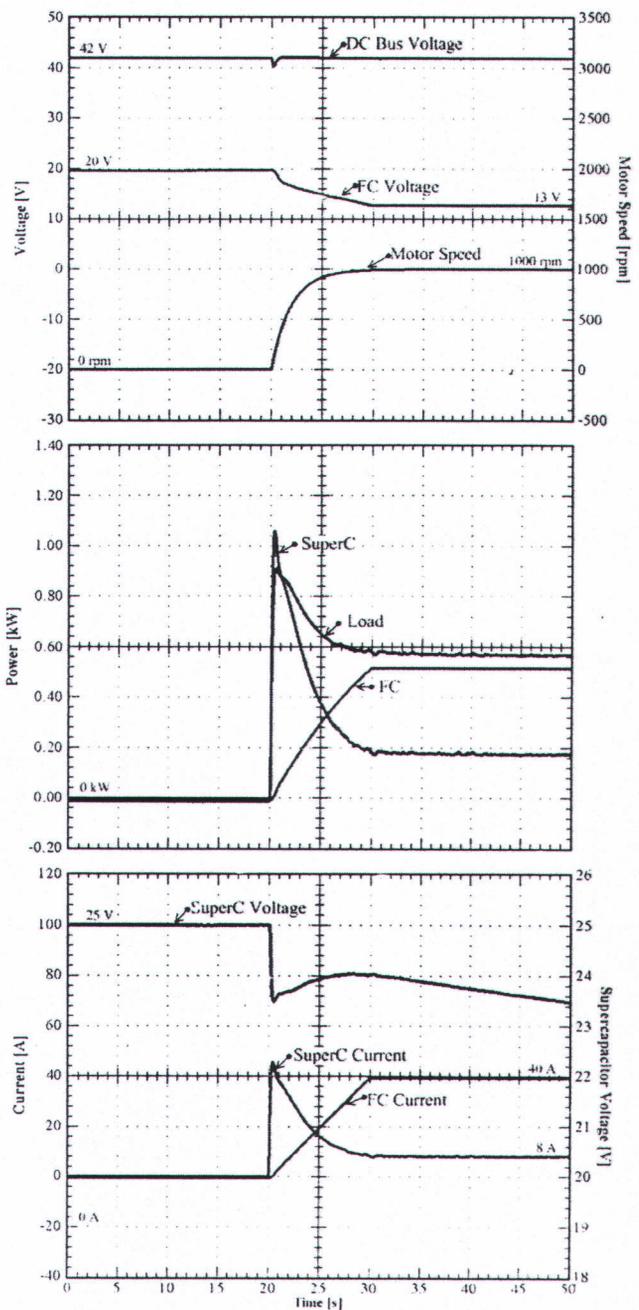


Fig. 12. FC/supercapacitor hybrid source response during motor startup to 1000 r/min.

be seen in Figs. 6 and 7 in simulation results (in per unit) and in Figs. 10–13 in experimental results, the powers are always balanced during dynamic and transient states. Importantly, the high dynamics during load steps are compensated by storage devices. For the FC/battery hybrid source, the stepped energy is naturally supplied or absorbed by the battery because the battery bank is directly connected to the dc bus based on the control algorithm of the unregulated dc bus voltage. In the case of the FC/supercapacitor hybrid source, the stepped energy is automatically supplied or absorbed by the supercapacitor because the proposed control algorithm is based on the regulated dc bus voltage. Then, the supercapacitor module functions as

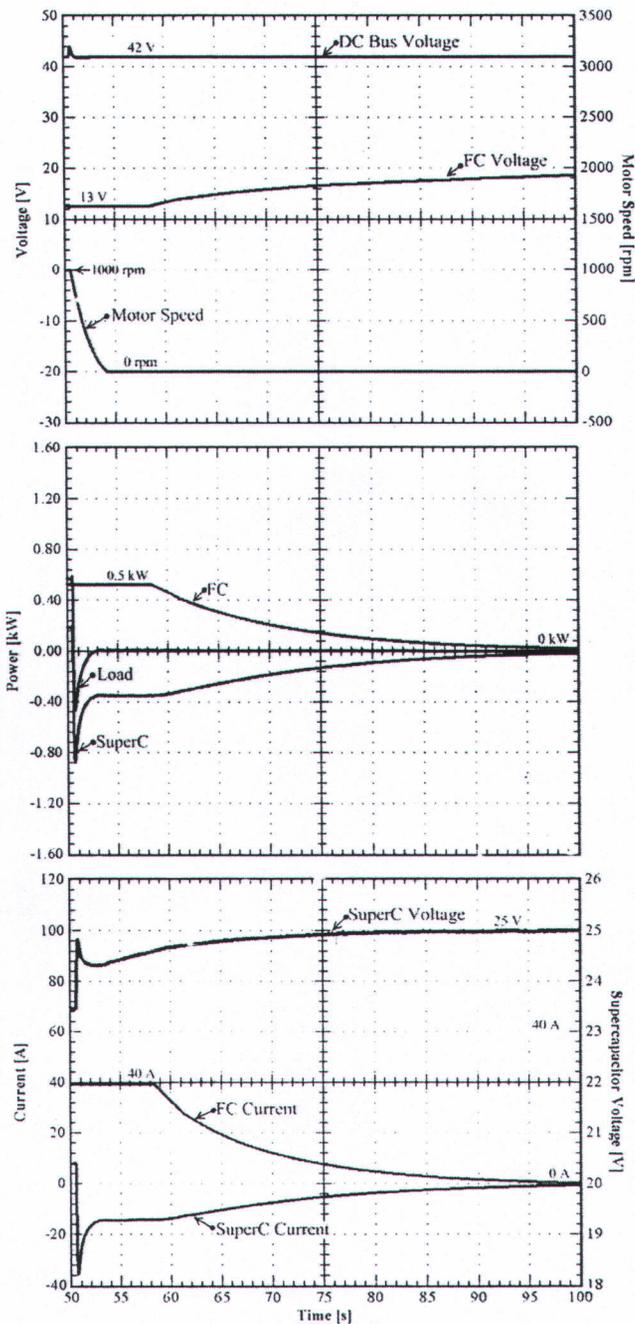


Fig. 13. FC/supercapacitor hybrid source response during motor braking from 1000 r/min.

the one supplying or absorbing the energy that is required to achieve the dc bus voltage.

## V. CONCLUSION

The advantages of an FC hybrid vehicle could include improved vehicle performance and fuel economy and lower system cost. The degree of hybridization benefits from 1) FC efficiency characteristics; 2) FC downsizing; 3) displacing FC tasks with the secondary source functionality; or 4) energy recovery through regenerative braking. This paper has studied

the role of the energy-storage device in FC hybrid vehicles to understand their potential impact on dynamic performances.

Experimental verifications with a small-scale hybrid test bench in the laboratory have evidently shown the possibility of improving the performance of the whole system and validated the proposed control algorithms: the FC/battery hybrid source and the FC/supercapacitor hybrid source.

In general, the FC/supercapacitor hybrid has better performance because the supercapacitor can more effectively assist the FC to meet the transient power demand (the supercapacitor can be charged or discharged at a high current, in which the battery cannot function), and high-current charges and discharges from the battery will reduce its lifetime as well.

Nonetheless, an FC hybrid vehicle with supercapacitors as the only energy storage will be deficient or even malfunction during the vehicle startup because of the startup time of a PEMFC of around 5–10 min, in which the battery has higher specific energy than the supercapacitor. Consequently, a more practical answer will be an FC/battery/supercapacitor hybrid power source [45] to increase the battery lifetime due to the reduction of high-current charges and discharges.

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## REFERENCES

- [1] P. Thounthong, B. Davat, and S. Raël, “Drive friendly,” *IEEE Power Energy Mag.*, vol. 6, no. 1, pp. 69–76, Jan./Feb. 2008.
- [2] K. Rajashekara, J. Grieve, and D. Daggett, “Hybrid fuel cell power in aircraft,” *IEEE Ind. Appl. Mag.*, vol. 14, no. 4, pp. 54–60, Jul./Aug. 2008.
- [3] W. M. Yan, H. S. Chu, M. X. Lu, F. B. Weng, G. B. Jung, and C. Y. Lee, “Degradation of proton exchange membrane fuel cells due to CO and CO<sub>2</sub> poisoning,” *J. Power Sources*, vol. 188, no. 1, pp. 141–147, Mar. 2009.
- [4] A. Khaligh, A. M. Rahimi, Y. J. Lee, J. Cao, A. Emadi, S. D. Andrews, C. Robinson, and C. Finnerty, “Digital control of an isolated active hybrid fuel cell/Li-ion battery power supply,” *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3709–3721, Nov. 2007.
- [5] P. Thounthong, S. Raël, and B. Davat, “Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle,” *J. Power Sources*, vol. 158, no. 1, pp. 806–814, Jul. 2006.
- [6] J. M. Corrêa, F. A. Farret, V. A. Popov, and M. G. Simões, “Sensitivity analysis of the modeling used in simulation of proton exchange membrane fuel cells,” *IEEE Trans. Energy Convers.*, vol. 20, no. 1, pp. 211–218, Jan./Mar. 2005.
- [7] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, “Fuel cell high-power applications,” *IEEE Ind. Electron. Mag.*, vol. 3, no. 1, pp. 32–46, Mar. 2009.
- [8] K. P. Adzakpa, K. Agbossou, Y. Dubé, M. Dostie, M. Fournier, and A. Poulin, “PEM fuel cells modeling and analysis through current and voltage transient behaviors,” *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 581–591, Jun. 2008.
- [9] C. Wang and M. H. Nehrir, “Load transient mitigation for stand-alone fuel cell power generation systems,” *IEEE Trans. Energy Convers.*, vol. 22, no. 4, pp. 864–872, Dec. 2007.
- [10] R. Gaynor, F. Mueller, F. Jabbari, and J. Brouwer, “On control concepts to prevent fuel starvation in solid oxide fuel cells,” *J. Power Sources*, vol. 180, no. 1, pp. 330–342, May 2008.
- [11] W. Schmittinger and A. Vahidi, “A review of the main parameters influencing long-term performance and durability of PEM fuel cells,” *J. Power Sources*, vol. 180, no. 1, pp. 1–14, May 2008.
- [12] B. Wahdame, D. Candusso, X. François, F. Harel, M. C. Péra, D. Hissel, and J. M. Kauffmann, “Analysis of a fuel cell durability test based on

- design of experiment approach," *IEEE Trans. Energy Convers.*, vol. 23, no. 4, pp. 1093–1104, Dec. 2008.
- [13] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell and supercapacitors association for distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3225–3233, Dec. 2007.
- [14] P. Corbo, F. Migliardini, and O. Veneri, "An experimental study of a PEM fuel cell power train for urban bus application," *J. Power Sources*, vol. 181, no. 2, pp. 363–370, Jul. 2008.
- [15] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2258–2267, Jun. 2008.
- [16] M. M. Flynn, P. McMullen, and O. Solis, "Saving energy using flywheels," *IEEE Ind. Appl. Mag.*, vol. 14, no. 6, pp. 69–76, Nov./Dec. 2008.
- [17] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237–2245, Jun. 2008.
- [18] J. Bauman and M. Kazerani, "A comparative study of fuel-cell-battery, fuel-cell-ultracapacitor, and fuel-cell-battery-ultracapacitor," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 760–769, Mar. 2008.
- [19] M. Ceraolo, A. di Donato, and G. Franceschi, "A general approach to energy optimization of hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1433–1441, May 2008.
- [20] A. Szumanowski and Y. Chang, "Battery management system based on battery nonlinear dynamics modeling," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1425–1432, May 2008.
- [21] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 148–155, Mar. 2008.
- [22] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721–2735, Sep. 2008.
- [23] A. Payman, S. Pierfederici, and F. Meibody-Tabar, "Energy control of supercapacitor/fuel cell hybrid power source," *Energy Convers. Manage.*, vol. 49, no. 6, pp. 1637–1644, Jun. 2008.
- [24] A. F. Burke, "Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 806–820, Apr. 2007.
- [25] J. R. Miller and A. F. Burke, "Electrochemical capacitors: Challenges and opportunities for real-world applications," *Electrochem. Soc. Interface*, vol. 17, no. 1, pp. 53–57, Spring 2008.
- [26] Y. S. Lee, W. Y. Wang, and T. Y. Kuo, "Soft computing for battery state-of-charge (SOC) estimation in battery string systems," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 229–239, Jan. 2008.
- [27] A. Kusko and J. DeDad, "Stored energy—Short-term and long-term energy storage methods," *IEEE Ind. Appl. Mag.*, vol. 13, no. 4, pp. 66–72, Jul./Aug. 2007.
- [28] M. Uzunoglu and M. S. Alam, "Modeling and analysis of an FC/UC hybrid vehicular power system using a novel-wavelet-based load sharing algorithm," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 263–272, Mar. 2008.
- [29] P. Thounthong, S. Raël, and B. Davat, "Test of a PEM fuel cell with low voltage static converter," *J. Power Sources*, vol. 153, no. 1, pp. 145–150, Jan. 2006.
- [30] S. Jain and V. Agarwal, "An integrated hybrid power supply for distributed generation applications fed by nonconventional energy sources," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 622–631, Jun. 2008.
- [31] S. Y. Choe, J. W. Ahn, J. G. Lee, and S. H. Baek, "Dynamic simulator for a PEM fuel cell system with a PWM DC/DC converter," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 669–680, Jun. 2008.
- [32] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel starvation: Analysis of a PEM fuel-cell system," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 52–59, Jul./Aug. 2009.
- [33] R. Chandrasekaran, W. Bi, and T. F. Fuller, "Robust design of battery/fuel cell hybrid systems—Methodology for surrogate models of Pt stability and mitigation through system controls," *J. Power Sources*, vol. 182, no. 2, pp. 546–557, Aug. 2008.
- [34] D. Gao, Z. Jin, and Q. Lu, "Energy management strategy based on fuzzy logic for a fuel cell hybrid bus," *J. Power Sources*, vol. 185, no. 1, pp. 311–317, Oct. 2008.
- [35] F. Baalbergen, P. Bauer, and J. A. Ferreira, "Energy storage and power management for typical 4Q-load," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1485–1498, May 2009.
- [36] A. Khaligh, "Realization of parasitics in stability of DC-DC converters loaded by constant power loads in advanced multiconverter automotive systems," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2295–2304, Jun. 2008.
- [37] A. Di Napoli, F. Crescimbeni, L. Solero, F. Caricchi, and F. G. Capponi, "Multiple-input DC–DC power converter for power-flow management in hybrid vehicles," in *Conf. Rec. 37th IEEE IAS Annu. Meeting*, Pittsburgh, PA, Oct. 13–17, 2002, vol. 3, pp. 1578–1585.
- [38] L. Solero, A. Lidozzi, and J. A. Pomilio, "Design of multiple-input power converter for hybrid vehicles," *IEEE Trans. Power Electron.*, vol. 20, no. 5, pp. 1007–1016, Sep. 2005.
- [39] I. Sadli, P. Thounthong, J. P. Martin, S. Raël, and B. Davat, "Behaviour of a PEMFC supplying a low voltage static converter," *J. Power Sources*, vol. 156, no. 1, pp. 119–125, May 2006.
- [40] Z. Jiang and R. A. Dougal, "A compact digitally controlled fuel cell/battery hybrid power source," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1094–1104, Jun. 2006.
- [41] M. Y. Avad, S. Pierfederici, S. Raël, and B. Davat, "Voltage regulated hybrid DC power source using supercapacitors as energy storage device," *Energy Convers. Manage.*, vol. 48, no. 7, pp. 2196–2202, Jul. 2007.
- [42] P. Thounthong, S. Raël, and B. Davat, "Supercapacitors as an energy storage for fuel cell automotive hybrid electrical system," *Int. J. Elect. Eng. Trans.*, vol. 1, no. 1, pp. 21–25, 2005.
- [43] M. Kim, Y. J. Sohn, W. Y. Lee, and C. S. Kim, "Fuzzy control based engine sizing optimization for a fuel cell/battery hybrid mini-bus," *J. Power Sources*, vol. 178, no. 2, pp. 706–710, Apr. 2008.
- [44] P. Thounthong, S. Raël, and B. Davat, "Analysis of supercapacitor as second source based on fuel cell power generation," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 247–255, Mar. 2009.
- [45] P. Thounthong, S. Raël, and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," *J. Power Sources*, vol. 193, no. 1, pp. 376–385, Aug. 2009.



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## Energy management of fuel cell/solar cell/supercapacitor hybrid power source

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### ABSTRACT

This study presents an original control algorithm for a hybrid energy system with a renewable energy source, namely, a polymer electrolyte membrane fuel cell (PEMFC) and a photovoltaic (PV) array. A single storage device, i.e., a supercapacitor (ultracapacitor) module, is in the proposed structure. The main weak point of fuel cells (FCs) is slow dynamics because the power slope is limited to prevent fuel starvation problems, improve performance and increase lifetime. The very fast power response and high specific power of a supercapacitor complements the slower power output of the main source to produce the compatibility and performance characteristics needed in a load. The energy in the system is balanced by d.c.-bus energy regulation (or indirect voltage regulation). A supercapacitor module functions by supplying energy to regulate the d.c.-bus energy. The fuel cell, as a slow dynamic source in this system, supplies energy to the supercapacitor module in order to keep it charged. The photovoltaic array assists the fuel cell during daytime. To verify the proposed principle, a hardware system is realized with analog circuits for the fuel cell, solar cell and supercapacitor current control loops, and with numerical calculation (dSPACE) for the energy control loops. Experimental results with small-scale devices, namely, a PEMFC (1200 W, 46 A) manufactured by the Ballard Power System Company, a photovoltaic array (800 W, 31 A) manufactured by the Ekarat Solar Company and a supercapacitor module (100 F, 32 V) manufactured by the Maxwell Technologies Company, illustrate the excellent energy-management scheme during load cycles.

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### 1. Introduction

Currently, most of the energy demand in the world is met by fossil and nuclear power plants. A small part is drawn from renewable energy technologies such as wind, solar, fuel cell, biomass and geothermal energy [1,2]. Wind energy, solar energy and fuel cells have experienced a remarkably rapid growth in the past ten years [3–5] because they are pollution-free sources of power. Additionally, they generate power near the load centres, which eliminates the need to run high-voltage transmission lines through rural and urban landscapes.

The cost of solar photovoltaic and fuel cell electricity is still high [6–8]. Nevertheless, with ongoing research, development and utilization of these technologies around the world, the costs of solar cells and fuel cell energy are expected to fall in the next few years. As for solar cell and fuel cell electricity producers, they now sell power

freely to end-users through truly open access to the transmission lines. For this reason, they are likely to benefit as much as other producers of electricity. Another benefit in their favour is that the cost of renewable energy falls as technology advances, whereas the cost of electricity from conventional power plants rises with inflation. The difference in their trends indicates that hydrogen and solar power will be more advantageous in future.

In the near future, the utility power system at a large scale will be supplied by renewable energy sources and storage device(s), i.e., *hybrid energy systems*, in order to increase their reliability and make them more effective. The specific properties of fuel cells and solar cells are as follows:

- The amount of power the fuel cell system delivers is controlled by the amount of current drawn from the system if the proper conditions for cell operation are maintained. When a large load is applied to the cells, the sudden increase in the current can cause the system to stall if the depleted oxygen or hydrogen cannot be replenished immediately and sufficiently. Cell starvation can lead to a system stall, permanent cell damage or

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**Nomenclature**

a.c.	alternating current
d.c.	direct current
FC	fuel cell
PV	photovoltaic
SC	supercapacitor
$C_{Bus}$	total capacitance at d.c.-bus (F)
$C_{SC}$	total capacitance of supercapacitor module (F)
$i_{Load}$	d.c.-bus load current (A)
$i_{FC}$	fuel cell current (A)
$i_{FCREF}$	fuel cell current reference (set-point) (A)
$i_{Sol}$	solar cell (photovoltaic) current (A)
$i_{SolREF}$	solar cell current reference (set-point) (A)
$i_{SC}$	supercapacitor current (A)
$i_{SCREF}$	supercapacitor current reference (set-point) (A)
$P_{Load}$	load power (W)
$P_{FC}$	fuel cell power (W)
$P_{FCa}$	fuel cell output power to d.c.-bus (W)
$P_{FCREF}$	fuel cell power reference (set-point) (W)
$P_{FCMax}$	maximum fuel cell power (W)
$P_{Sol}$	solar cell (photovoltaic) power (W)
$P_{Sola}$	solar cell output power to d.c.-bus (W)
$P_{SolREF}$	solar cell power reference (set-point) (W)
$P_{SolMax}$	maximum solar cell power (W)
$P_{SC}$	supercapacitor power (W)
$P_{SCa}$	supercapacitor output power to d.c.-bus (W)
$P_{SCREF}$	supercapacitor power reference (set-point) (W)
$P_{SCMax}$	maximum supercapacitor power (W)
$v_{Bus}$	d.c.-bus voltage (V)
$v_{FC}$	fuel cell voltage (V)
$v_{Sol}$	solar cell (photovoltaic) voltage (V)
$v_{SC}$	supercapacitor voltage (V)
$y_{Bus}$	d.c.-bus energy (J)
$y_{BusREF}$	d.c.-bus energy reference (set-point) (J)
$y_{SC}$	supercapacitor energy (J)
$y_{SCREF}$	supercapacitor energy reference (set-point) (J)
$y_T$	total energy at d.c.-bus and supercapacitor (J)
$r_{FC}$	equivalent series resistance in fuel cell converter ( $\Omega$ )
$r_{Sol}$	equivalent series resistance in solar cell converter ( $\Omega$ )
$r_{SC}$	equivalent series resistance in supercapacitor converter ( $\Omega$ )
$u$	input variable vector
$x$	state-variable vector
$y$	output vector
$\varphi(\cdot), \psi(\cdot), \phi(\cdot)$	smooth mapping functions

reduced cell lifetime. To protect the fuel cells from overloading and starvation, especially during transient conditions, excessive oxygen and hydrogen can be supplied to the cells during the steady-state operation, which increases the reserve of available power in anticipation of a load increase. This strategy, however, is conservative and leads to increased parasitic losses, decreased air utilization and thereby compromised system performance. Therefore, the fuel cell power or current slope must be limited to prevent a fuel cell stack from experiencing the fuel starvation phenomenon and to optimize the system, for example,  $4 A s^{-1}$  for a 0.5 kW, 12.5-V PEMFC [9], and 5, 10 and  $50 A s^{-1}$  for a 20 kW, 48-V PEMFC [10].

- The output power of solar cells fluctuates considerably depending on solar radiation, weather conditions and temperature [11,12].

Therefore, in order to supply electric power to fluctuating loads with a hybrid system composed of the above-mentioned fuel cell and solar cell, an electric energy-storage system is needed to compensate for the gap between the output from the renewable energy sources and the load, in addition to the collaborative load sharing among those energies [13–15].

Moreover, hydrogen as an energy storage media has the potential to address both daily and seasonal buffering requirements. Systems that employ an electrolyzer to convert excess electricity to hydrogen coupled with hydrogen storage and regeneration using a fuel cell can, in principle, provide power with zero (or near zero) emissions. Hydrogen production by solar energy is a 'renewable-regenerative system' [4], and this process is known as the electrolysis process. The basic principle is the following: when the photovoltaic input power exceeds the load power demand, the system controller determines that the energy should be directed to hydrogen production. In this kind of operation, i.e., a solar-based renewable-regenerative system, almost half of the solar input energy is directed to hydrogen production and converted with 60% energy efficiency [4].

Based on present storage device technology, battery design has to supply the trade-off between specific energy, specific power and cycle life. The difficulty in obtaining high values of these three parameters has led to some suggestions that the energy-storage system of distributed generation systems should be a hybridization of an energy source and a power source [16,17]. The energy source, mainly fuel cells and solar cells in this study, has high specific energy, whereas the power source has high specific power. The power sources can be recharged from the main energy source(s) when there is less demand. The power source that has received wide attention is the supercapacitor (or 'ultracapacitor', or 'electrochemical double-layer capacitor') [18–20].

The enhancements in the performance of renewable energy source power systems that are gained by adding energy storage are all derived from the ability to shift the system output. Firming-up the renewable system is accomplished by ensuring that energy is available when there is a demand for it rather than being limited by the availability of the renewable resource. As a result, the system output may need to be shifted to periods when the hydrogen and/or the sun, for example, are not available [21]. Depending on the size and type of the energy-storage system and the load, it may be possible to provide all of the power needed to support the load. A much more common scenario is for the energy storage to simply provide enough power for applications, like peak shaving, without having full load support capability. The energy-storage system may also provide sufficient energy to ride out electric service interruptions that range from a few seconds to a few hours. This is especially important for service disruptions that occur when the renewable resource is not available.

In this study, a fuel cell/photovoltaic/supercapacitor hybrid power source is proposed. A power electronic converter structure, energy management and innovative energy control law are presented. To authenticate the proposed principle, the hardware system is realized by analog circuits and digital estimation with a dSPACE controller. Experimental results obtained with small-scale devices illustrate the system performance.

**2. Renewable energy hybrid system**

**2.1. System configuration**

The power converter structure of the system is shown in Fig. 1. Fuel cell and solar cell power-generating systems may provide direct or alternating current (d.c. or a.c.) to satisfy application-specific power needs (Fig. 1). The current, voltage and power quality

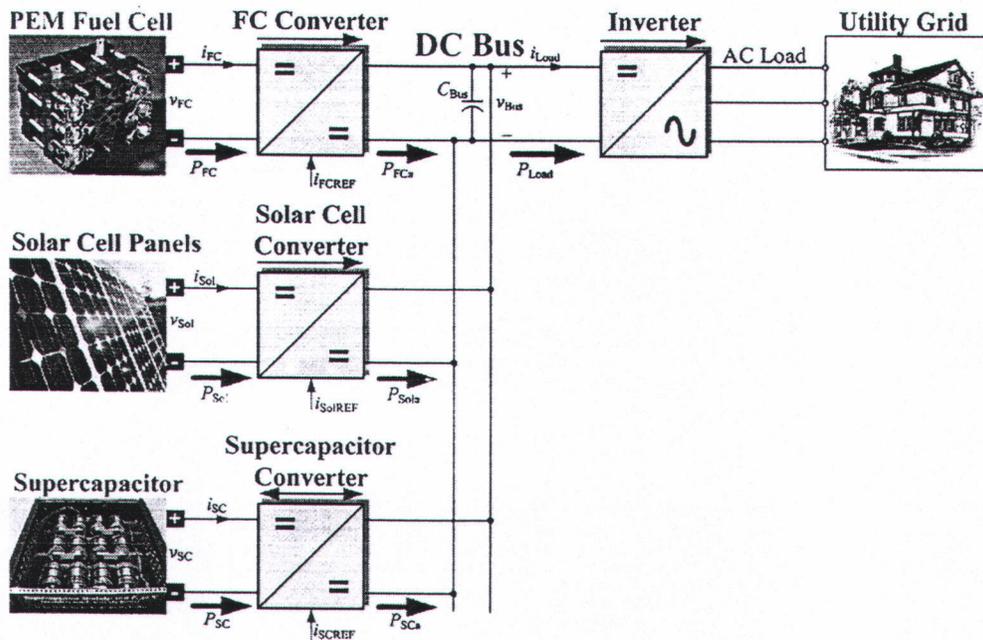


Fig. 1. Proposed hybrid energy system supplied by fuel cell, solar cell and supercapacitor, where  $p_{Load} (= v_{Bus} \times i_{Load})$ ,  $v_{Bus}$  and  $i_{Load}$  are load power, d.c.-bus voltage and d.c.-bus load current, respectively.  $p_{FC} (= v_{FC} \times i_{FC})$ ,  $v_{FC}$  and  $i_{FC}$  are fuel cell power, voltage and current, respectively.  $p_{Sol} (= v_{Sol} \times i_{Sol})$ ,  $v_{Sol}$  and  $i_{Sol}$  are solar cell power, voltage and current, respectively.  $p_{SC} (= v_{SC} \times i_{SC})$ ,  $v_{SC}$  and  $i_{SC}$  are supercapacitor power, voltage, and current, respectively.  $p_{FCa}$ ,  $p_{Sola}$  and  $p_{SCa}$  are the output powers to d.c. link from converters of fuel cell, solar cell and supercapacitor, respectively.  $i_{FCREF}$ ,  $i_{SolREF}$ ,  $i_{SCREF}$  are the current references of the fuel cell, solar cell and supercapacitor converters, respectively.

are controlled by electronic power-conditioning systems. Generally, voltage regulators and d.c.–d.c. converters (chopper circuits) are used to control and adjust the fuel cell and photovoltaic d.c. output voltages to useful values [22,23].

The voltages of the fuel cell and solar cell vary with the current drawn by the load and decrease significantly at high load currents [24]. Therefore, a power-electronics system is needed to process the raw output power from the stack or panel and provide power to the load at a constant d.c. or a.c. voltage. Typically, the power-electronics systems include multiple interconnected power converters: for example, a d.c.–d.c. converter is often followed by a d.c.–a.c. converter for stationary applications [25]. The switching scheme in such power converters can be based on pulse-width modulation (PWM), resonant, quasi-resonant, soft-switched, or line-commutated switching [26–28]. Furthermore, the topological structures of these converters can vary dramatically [29].

The supercapacitor bank is always connected to the d.c.-bus by means of a two-quadrant d.c.–d.c. converter (bidirectional converter), a ‘supercapacitor converter’. The supercapacitor power can be positive or negative, which allows energy to be transferred in both directions [30].

An inverter is used to convert the d.c. voltage to a useful a.c. voltage. It may operate as grid-independent or with grid-synchronization. Then, the solar cell supplies all its output power to the d.c.-bus, and the fuel cell supplies a slowly fluctuating power difference between the load power  $p_{Load}$  demand and the solar cell output power. A supercapacitor storage device can compensate for both a sudden change in the load demand and rapidly fluctuating solar cell output power caused by solar radiation; therefore, the load is supplied with stable power.

As depicted in Fig. 1, the proposed system has a multi-source structure (or cascade scheme). The cascaded structure can lead to interactions between converters that cause the system to be unstable, if they are designed separately. This problem has been studied during the past decade. In this case, to study interactions between the converters, impedance criteria are often used to determine the

stability of the cascaded system. Nonetheless, the technique only proves the asymptotic stability around a given operating point. The large signal stability properties or the behaviour of the system in the case of oversized disturbances are not considered in this model. In this paper, a non-linear control algorithm based on the differential flatness principle of the renewable power plant is proposed. Design controller parameters are independent of the operating point. Interactions between the converters are taken into account by the controllers, and high dynamics in perturbation rejection are accomplished.

## 2.2. Energy management

For reasons of safety and dynamics, the fuel cell, solar cell and supercapacitor converters are usually controlled primarily by inner current-regulation loops [17]. The dynamics of current-regulation loops are much faster than those of outer control loops, which are described later. Therefore, the fuel cell current  $i_{FC}$ , the solar cell current  $i_{Sol}$  and the supercapacitor current  $i_{SC}$  are considered to follow their references  $i_{FCREF}$ ,  $i_{SolREF}$  and  $i_{SCREF}$  perfectly.

Energy management of multi-power sources has already been studied recently, for example, Feroldi et al. [31] studied control (based on efficiency map) of a fuel cell/supercapacitor hybrid power source for vehicle applications, Payman et al. [32] studied control of a regulated d.c. voltage supplied by a fuel cell and supercapacitor storage device based on a differential flatness system, and Thounthong et al. addressed a regulated d.c.-bus voltage fuel cell/supercapacitor hybrid source [33], a regulated d.c.-bus voltage fuel cell/battery/supercapacitor hybrid source [34] and an unregulated d.c.-bus voltage fuel cell/battery hybrid source [14].

Thus, in the proposed system depicted in Fig. 1, there are two-voltage variables, or two-energy variables, to be regulated. The d.c.-bus energy  $y_{Bus}$  is the most important variable, and the supercapacitor storage energy  $y_{SC}$  is the next most important. Therefore, based on the previous work described above, it is proposed to utilize supercapacitors, which are the fastest energy source in the pro-

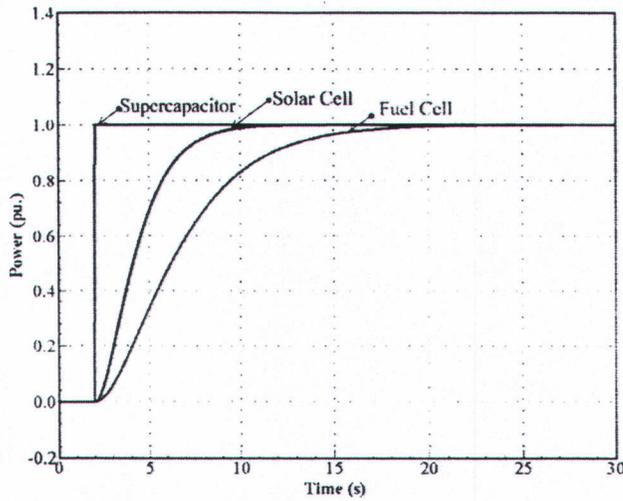


Fig. 2. Dynamic classification for proposed hybrid power source.

posed system, to supply the energy for the d.c.-bus [33,34]. Thus, the fuel cell (as the slowest dynamic device) and solar cell supply energy for both the d.c.-bus capacitor  $C_{Bus}$  and the supercapacitors  $C_{SC}$  to keep them charged.

At the d.c. link, there are three sources that supply energy at the same time. Therefore, the dynamics of the three sources must be classified in order to guarantee system stability [34], as illustrated in Fig. 2. Note that the power unit in Fig. 2 is the normalized unit (or per-unit [pu]). Thus, the defined dynamic classification depicted in Fig. 2 is obtained from the simulation result using Matlab–Simulink, and the experimental results of the power source dynamics are presented after the performance validation section. The supercapacitor is operated as the highest dynamic power source to provide the micro-cycles and the fast dynamic power supply. It can withstand a very large number of charge–discharge cycles without degradation (or virtually infinite cycles) [33,35]. The fuel cell generator is operated as the lowest dynamic power source. The fuel cell current or power slope must be limited to avoid the fuel starvation phenomenon. The fuel cell limited current or power slope has been experimentally determined to be the highest slope of an operating fuel cell system, where no fuel starvation occurs in order to improve its lifetime [33,34]. The photovoltaic generator is between the fuel cell and supercapacitor in the dynamic classification.

### 2.2.1. Principle of differential flatness theory

A non-linear control algorithm based on the flatness properties [36–38] of the system is proposed. According to the flatness-control law, the tuning controller parameters are independent of the operating point [32]. According to Fliess et al. [39,40], an independent dynamic system is considered to be differentially flat if an output  $y$  is given by:

$$y = \phi(x, u, \dot{u}, \dots, u^{(\alpha)}), \quad y \in \mathbb{R}^m \quad (1)$$

such that the state  $x$  and controls  $u$  (or inputs) can be written as:

$$x = \varphi(y, \dot{y}, \dots, y^{(\beta)}), \quad x \in \mathbb{R}^n \quad (2)$$

$$u = \psi(y, \dot{y}, \dots, y^{(\beta+1)}), \quad u \in \mathbb{R}^m \quad (3)$$

where  $\varphi(\cdot)$ ,  $\psi(\cdot)$ ,  $\phi(\cdot)$  are the smooth mapping functions,  $\alpha$  and  $\beta$  are a finite number of their time derivatives, and  $(n, m) \in \mathbb{N}$ . Moreover, it is assumed that  $m \leq n$ .

The output  $y$  is called a *flat output*. Thus, a dynamic system is, in nature, differentially flat if it is equivalent to a system without dynamics, i.e., a static system. In other words, there are no differential constraints in output space. The apparent advantage of a

differentially flat system is that every trajectory in the output space is feasible; therefore, trajectory generation is theoretically simpler in terms of the flat outputs. For this reason, by using the flatness estimation in power electronic applications, interactions between the converters are taken into account by the flatness-control law and high dynamics in perturbation elimination are achieved.

### 2.2.2. d.c.-Bus energy control

Based on the flatness-control, the electrostatic energy  $y_{Bus}$  stored in the total d.c.-bus capacitor  $C_{Bus}$  is considered as the flat output variable (Eq. (1)), i.e.:

$$y_{Bus} = \frac{1}{2} C_{Bus} v_{Bus}^2 \quad (4)$$

It is assumed that the supercapacitor current follows its reference value perfectly. Thus:

$$i_{SC} = i_{SCREF} = \frac{p_{SC}}{v_{SC}} = \frac{p_{SCREF}}{v_{SC}} \quad (5)$$

where  $p_{SCREF}$  is the control variable of the reduced system described in Eq. (3).

Therefore, the state variable  $v_{Bus}$  may be put into a form similar to that in Eq. (2):

$$v_{Bus} = \sqrt{\frac{2y_{Bus}}{C_{Bus}}} = \varphi_1(y) \quad (6)$$

To obtain a relationship between the control variable  $p_{SC}$  and the flat output variable  $y_{Bus}$ , the differential equation verified by the reduced model from Fig. 1 is written as:

$$\dot{y}_{Bus} = p_{FCa} + p_{Sola} + p_{SCa} - p_{Load} \quad (7)$$

where

$$p_{FCa} = p_{FC} - r_{FC} \left( \frac{p_{FC}}{v_{FC}} \right)^2 \quad (8)$$

$$p_{Sola} = p_{Sol} - r_{Sol} \left( \frac{p_{Sol}}{v_{Sol}} \right)^2 \quad (9)$$

$$p_{SCa} = p_{SC} - r_{SC} \left( \frac{p_{SC}}{v_{SC}} \right)^2 \quad (10)$$

$r_{FC}$  is the total equivalent series resistance in the fuel cell converter. Here, only static resistance loss is considered [32].  $r_{Sol}$  is the total equivalent series resistance in the solar cell converter.  $r_{SC}$  is the total equivalent series resistance in the supercapacitor converter.

It follows that:

$$p_{SCREF} = 2p_{SCMax} \left[ 1 - \sqrt{1 - \left( \frac{\dot{y}_{Bus} + p_{Load} - p_{FCa} - p_{Sola}}{p_{SCMax}} \right)^2} \right] = \psi_1(y, \dot{y}) \quad (11)$$

where

$$p_{SCMax} = \frac{v_{SC}^2}{4r_{SC}} \quad (12)$$

$$p_{Load} = v_{Bus} i_{Load} = \sqrt{\frac{2y_{Bus}}{C_{Bus}}} i_{Load} \quad (13)$$

$p_{SCMax}$  is the limited maximum power from the supercapacitor module.

Thus, it is apparent that  $p_{SC} = \psi_1(y, \dot{y})$ , which corresponds with Eq. (3), and the proposed reduced system with the control variable  $p_{SC}$  can be considered to be a flat system associated with  $y_{Bus}$  as the flat output variable.

To ensure the control of the flat output variable  $y_{Bus}$  to its reference trajectory  $y_{BusREF}$ , the following control law is based on the

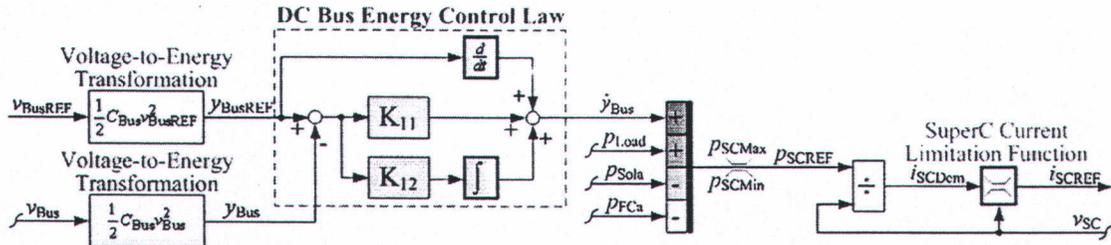


Fig. 3. Proposed d.c.-bus energy control loop for fuel cell/solar cell/supercapacitor hybrid source.

well-known second-order control law:

$$(\dot{y}_{Bus} - \dot{y}_{BusREF}) + K_{11}(y_{Bus} - y_{BusREF}) + K_{12} \int_0^t (y_{Bus} - y_{BusREF}) d\tau = 0 \quad (14)$$

where  $K_{11}$ , and  $K_{12}$  are the controller parameters. Defining  $e_{y_{Bus}} = y_{Bus} - y_{BusREF}$ ,  $K_{11} = 2\zeta\omega_n$ , and  $K_{12} = \omega_n^2$  gives:

$$\ddot{e}_{y_{Bus}} + 2\zeta\omega_n\dot{e}_{y_{Bus}} + \omega_n^2 e_{y_{Bus}} = 0 \quad (15)$$

It is obvious that the control system is stable for  $K_{11}, K_{12} > 0$ . Based on the power electronic constant switching frequency  $f_s$  and a cascade control structure, the outer control loop (here the d.c.-bus energy control) must operate at a cut-off frequency  $f_e \ll f_c$  (a cut-off frequency of the supercapacitor current loop or power loop)  $\ll f_s$  [41]. The d.c.-bus energy control loop detailed above is portrayed in Fig. 3.

The d.c.-bus energy control law generates a supercapacitor power reference  $p_{SCREF}$ . This signal is then divided by the measured supercapacitor voltage  $v_{SC}$  and limited to maintain the supercapacitor voltage within an interval  $[V_{SCMin}, V_{SCMax}]$  by limiting the supercapacitor charging current or discharging current, as presented in the block "SuperC Current Limitation Function" [33]. The higher voltage value  $V_{SCMax}$  of this interval corresponds to the maximum voltage of the storage device. Generally, the lower voltage value  $V_{SCMin}$  is chosen as  $V_{SCMax}/2$ , which causes only 25% of the energy in the supercapacitor bank to remain [33]; as a result, the supercapacitor discharge becomes ineffective. This results in the supercapacitor current reference  $i_{SCREF}$ .

### 2.2.3. Supercapacitor energy control

The classical electrostatic energy storage  $y_{SC}$  in the supercapacitor is expressed by:

$$y_{SC} = \frac{1}{2} C_{SC} v_{SC}^2 \quad (16)$$

where  $C_{SC}$  is the supercapacitor capacitance (refer to Fig. 1), and  $v_{SC}$  is the supercapacitor voltage.

Again, based on the flatness-control, the total electrostatic energy  $y_T$  stored in the total d.c.-bus capacitor  $C_{Bus}$  and the supercapacitor  $C_{SC}$  is taken as the flat output variable (Eq. (1)), i.e.:

$$y_T = y_{Bus} + y_{SC} = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2 \quad (17)$$

It is again assumed that the fuel cell and photovoltaic currents follow their reference values perfectly. Thus:

$$i_{FC} = i_{FCREF} = \frac{p_{FC}}{v_{FC}} = \frac{p_{FCREF}}{v_{FC}} \quad (18)$$

$$i_{Sol} = i_{SolREF} = \frac{p_{Sol}}{v_{Sol}} = \frac{p_{SolREF}}{v_{Sol}} \quad (19)$$

where  $p_{FCREF}$  and  $p_{SolREF}$  are the control variables of the reduced system (Eq. (3)).

Thus, the state variable  $v_{SC}$  may be put into a form similar to that of Eq. (2):

$$v_{SC} = \sqrt{\frac{2(y_T - y_{Bus})}{C_{SC}}} = \varphi_2(y) \quad (20)$$

The differential equation verified by the reduced model from Fig. 1 is:

$$\dot{y}_T = p_{Ta} - p_{Load} \quad (21)$$

where

$$p_{Ta} = p_{FCa} + p_{Sola} = p_T - r_T \left( \frac{p_T}{v_T} \right)^2 \quad (22)$$

For a fuel cell and a solar cell that are combined as an energy source to supply energy to a d.c.-bus and supercapacitor,  $v_T$  is defined as presented in Eq. (22) and  $r_T$  represents the total losses in the fuel cell and photovoltaic converters.

Therefore:

$$p_{TREF} = 2p_{TMax} \left[ 1 - \sqrt{1 - \left( \frac{\dot{y}_T + p_{Load}}{p_{TMax}} \right)} \right] = \psi_2(y, \dot{y}) \quad (23)$$

where

$$p_{TMax} = \frac{v_T^2}{4r_T} \quad (24)$$

In fact:

$$p_{TMax} = p_{FCMax} + p_{SolMax} \quad (25)$$

$p_{FCMax}$  is the maximum fuel cell power.  $p_{SolMax}$  is the maximum photovoltaic power.

Photovoltaic power systems require some specific estimation algorithms to deliver the maximum power point (MPP) because the output features of a solar cell vary with environmental changes in irradiance and temperature. Many previous investigations have presented different techniques for maximum power point tracking (MPPT) of photovoltaic arrays [42–44]. It is beyond the scope of this study to present the MPPT algorithm here, though it is similar to Eq. (14). Because the supercapacitor energy storage has a large capacity and the supercapacitor energy is defined as a slower dynamic variable than the d.c.-bus energy variable, the total (supercapacitor) energy control law is defined as:

$$(\dot{y}_T - \dot{y}_{TREF}) + K_{21}(y_T - y_{TREF}) = 0 \quad (26)$$

The supercapacitor energy control loop is shown in Fig. 4. The total energy control law generates a total power reference  $p_{TREF}$ . First,  $p_{TREF}$  is considered to be the photovoltaic power reference  $p_{SolarREF}$ . It must be limited in level, within an interval maximum  $p_{SolarMax}$  (MPP) and minimum  $p_{SolarMin}$  (set to 0W), and have limited dynamics to respect constraints in the dynamic classification (Fig. 2). Here, the second-order delay [34] is selected as a photovoltaic power dynamic limitation, as illustrated in Fig. 4. Second, the difference between the total power reference  $p_{TREF}$  and the



**Table 1**  
d.c.-bus energy control loop parameters.

Parameter	Value	
$v_{BusREF}$	60	V
$C_{Bus}$	12,200	$\mu F$
$K_{11}$	450	$rad\ s^{-1}$
$K_{12}$	22,500	$rad\ s^{-2}$
$r_{FC}$	0.14	$\Omega$
$r_{Sol}$	0.12	$\Omega$
$r_{SC}$	0.10	$\Omega$
$V_{SCMax}$	32	V
$V_{SCMin}$	15	V
$i_{SCRated}$	150	A

**Table 2**  
Supercapacitor energy control loop parameters.

Parameter	Value	
$v_{SCREF}$	25	V
$C_{SC}$	100	F
$K_{21}$	0.1	$WJ^{-1}$
$p_{SolMax} (rated)$	800	W
$p_{SolMin}$	0	W
$i_{SolMax} (rated)$	28	A
$i_{SolMin}$	0	A
$\zeta_2$	1	
$\omega_{n2}$	0.8	$rad\ s^{-1}$
$p_{FCMax}$	500	W
$p_{FCMin}$	0	W
$i_{FCMax} (rated)$	46	A
$i_{FCMin}$	0	A
$\zeta_1$	1	
$\omega_{n1}$	0.4	$rad\ s^{-1}$

each bidirectional converter is 25 kHz. The supercapacitor current, which flows across the storage device, can either be positive or negative, which allows energy to be transferred in both directions.

3.2. Control description

Measurements of the fuel cell current  $i_{FC}$ , the solar cell current  $i_{Sol}$ , the supercapacitor current  $i_{SC}$ , the load current  $i_{Load}$ , the d.c. link voltage  $v_{Bus}$ , the fuel cell voltage  $v_{FC}$ , the solar cell voltage  $v_{Sol}$ , and the supercapacitor voltage  $v_{SC}$  are collected with zero-flux Hall effect sensors.

The fuel cell, the solar cell and the supercapacitor current-regulation loops were realized by analog circuits to function at a high bandwidth. Parameters associated with the d.c.-bus energy regulation loop and the supercapacitor energy regulation loop can be seen in Tables 1 and 2, respectively. The fuel cell power dynamic delay is shown in Table 2; this value was experimentally determined as the highest power slope of the FC system, where no fuel starvation occurs. It must be noted here that, for the small-

test bench, the fuel cell maximum power  $p_{FCMax}$  is set at 500 W; but, the rated fuel cell power considered here is 1200 W. Further, these two energy control loops, which generate current references  $i_{FCREF}$ ,  $i_{SolREF}$  and  $i_{SCREF}$  are implemented on the real time card dSPACE DS1104 through the mathematical environment of Matlab–Simulink with a sampling frequency of 25 kHz.

3.3. Experimental results

The studied d.c.-bus of 60 V is only connected to an electronic load. To validate the dynamics of the power (current) regulation loops for each power source, Figs. 6–8 present waveforms that are obtained during the stepped power demand. Fig. 6 illustrates the fuel cell power demand, power response, voltage and current. Fig. 7 contains the photovoltaic power demand, power response,

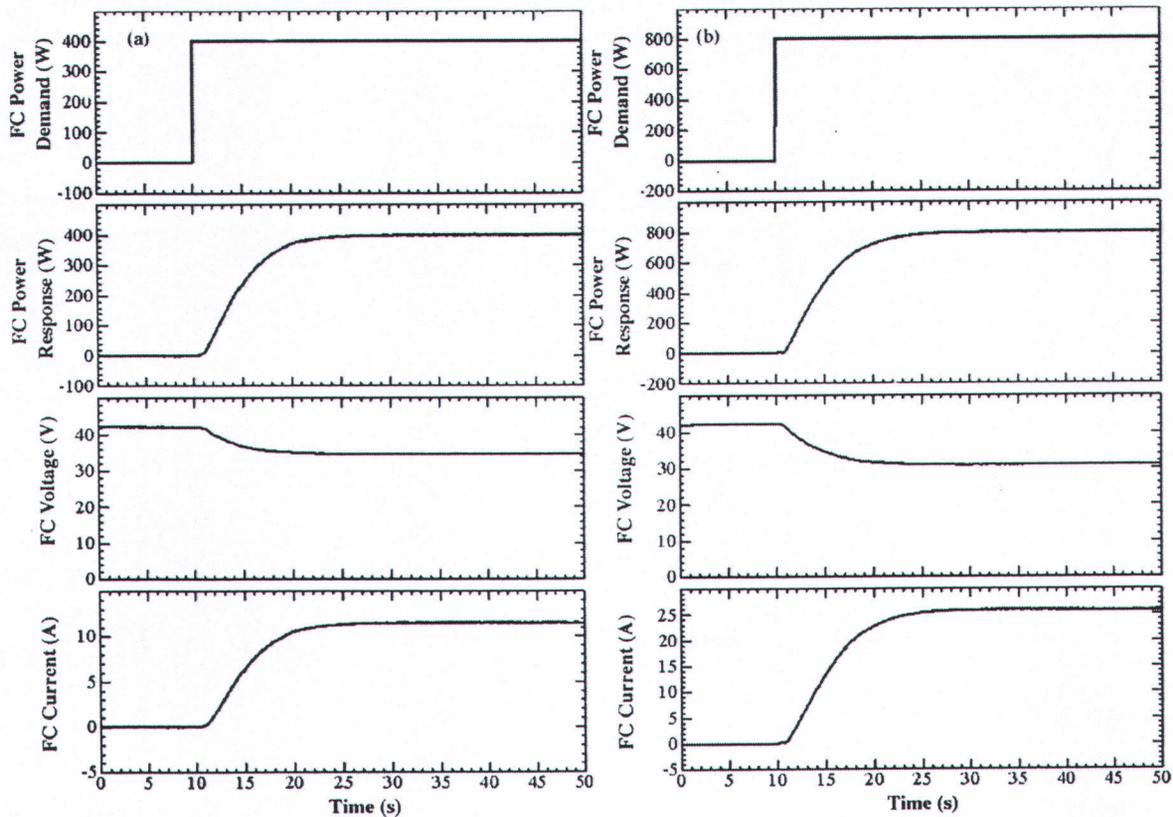


Fig. 6. Dynamic identification of fuel cell power control loop.

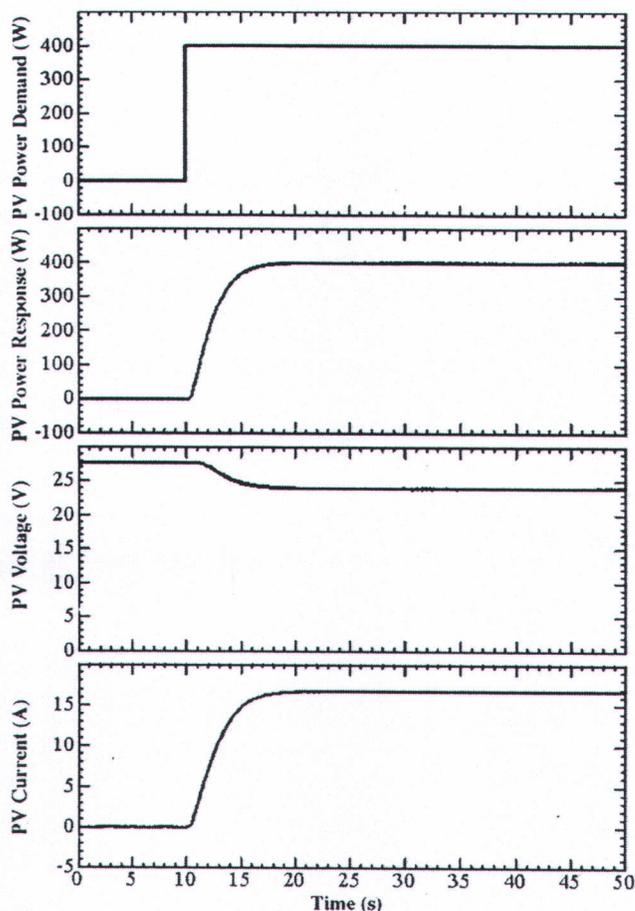


Fig. 7. Dynamic identification of photovoltaic power control loop.

voltage and current. Finally, Fig. 8 illustrates the supercapacitor power demand, power response, voltage and current. Because the fuel cell and photovoltaic powers are intentionally limited by the control algorithm (refer to Fig. 4: 'solar cell dynamic power limitation' and 'fuel cell power dynamic limitation'), a smooth transition of the power responses of the fuel cell and photovoltaic sources is observed, while the supercapacitor power dynamics are very fast. The supercapacitor can supply power from 0 to 400 W in 50 ms. It is clear that the fast response of the supercapacitor storage device can be operated with the fuel cell and solar cell main generators in order to improve system performance. The data in Fig. 6 also confirm that the fuel cell is controlled to avoid the fuel starvation phenomenon.

Because flatness-based control is model-based, it may have some sensitivity to errors in the model parameters. To authenticate its robustness, the flatness-based control was tested with the exact model parameters ( $r_{FC} = 0.14 \Omega$ ,  $r_{Sol} = 0.12 \Omega$ ,  $r_{SC} = 0.10 \Omega$ ) and in the lossless parameters case ( $r_{FC} = 0 \Omega$ ,  $r_{Sol} = 0 \Omega$ ,  $r_{SC} = 0 \Omega$ ). In the case of no losses, this leads to a drastically less complex estimation of the control law (Eqs. (8)–(11)). Comparisons (robustness) between the accurate parameters and the error parameters are given in Fig. 9. They generate waveforms that are obtained during the large load step from 0 to 500 W and show the d.c.-bus voltage, the load power (disturbance), the supercapacitor power, and the supercapacitor voltage (storage SOC). Because the power of the fuel cell and the solar cells are intentionally limited, the supercapacitor supplies the transient load power demand. Similar waveforms are seen in Fig. 9(a) and (b). The d.c.-bus voltage (d.c. link stabilization) is minimally influenced by the large step in load power.

Clearly the performance of the control system is hardly affected by the considered error in model parameters. Experimental testing demonstrates that errors in these parameters have relatively little effect on regulation performance. It is therefore concluded that the non-linear differential flatness-based approach provides an absolutely robust controller in this application.

Waveforms obtained during the large load cycle are presented in Fig. 10. The data show the d.c.-bus voltage, the fuel cell voltage, the photovoltaic voltage, the load power, the supercapacitor power, the fuel cell power, the photovoltaic power, the supercapacitor current, the fuel cell current, the photovoltaic current, and the supercapacitor voltage (or the supercapacitor SOC). In the initial state, the small load power is equal to 100 W, and the storage device is fully charge, i.e.,  $v_{SC} = 25$  V; as a result, both the fuel cell and supercapacitor powers are zero, and the photovoltaic source supplies power for the load of 100 W. At  $t = 40$  s, the load power steps to the final constant power of around 900 W (positive load power transition). The following observations are made:

- The supercapacitor supplies most of the 900 W power that is required during the transient step load.
- Simultaneously, the photovoltaic power increases with limited dynamics to a maximum power point (MPP) of around 300 W, which is limited by the maximum power point tracker (MPPT).
- Concurrently, the fuel cell power increases with limited dynamics to a maximum power of 500 W.
- The input from the supercapacitor, which supplies most of the transient power that is required during the stepped load, slowly decreases and the unit remains in a discharge state after the load step because the steady-state load power (approximately 900 W) is greater than the total power supplied by the fuel cell and photovoltaic array.

At  $t = 100$  s, the supercapacitor voltage is equal to 19 V. As a result, the supercapacitor supplies its stored energy  $y_{SC}$  to the d.c.-bus. This energy  $y_{SC\_Supply}$  is estimated to be:

$$y_{SC\_Supply} = \frac{1}{2} C_{SC} v_{SC}^2(t = 40 \text{ s}) - \frac{1}{2} C_{SC} v_{SC}^2(t = 100 \text{ s}) = 13.20 \text{ kJ} \quad (27)$$

The load power is reduced from the high constant power of 900 W to the low constant power of 100 W (negative load power transition). As a result, the supercapacitor changes from discharging to charging and demonstrates the following four phases:

- First, the fuel cell and photovoltaic array still supply their constant maximum powers to drive the load and to charge the supercapacitor.
- Second, at  $t = 110$  s, the supercapacitor is approaching full charge, i.e.,  $v_{SC} = 23$  V. Consequently, the fuel cell power is reduced with limited power dynamics.
- Third, at  $t = 120$  s, the supercapacitor is nearly fully charged, i.e.,  $v_{SC} = 24$  V. As a result, the photovoltaic power is reduced with limited power dynamics.
- Fourth, at  $t = 160$  s, the supercapacitor is fully charged, i.e.,  $v_{SC} = v_{SCREF} = 25$  V. After slowly decreasing, the photovoltaic power remains at a constant power of 100 W for the load power demanded. Furthermore, the fuel cell and supercapacitor powers are zero.

It is evident that the d.c.-bus voltage waveform is stable during the large load cycle, which is critically important when employing supercapacitors to improve the dynamic performance of the whole system using the proposed control law.

Finally, Fig. 11 presents waveforms that are obtained during the long load cycles measured on 5 December, 2009. The waveforms are

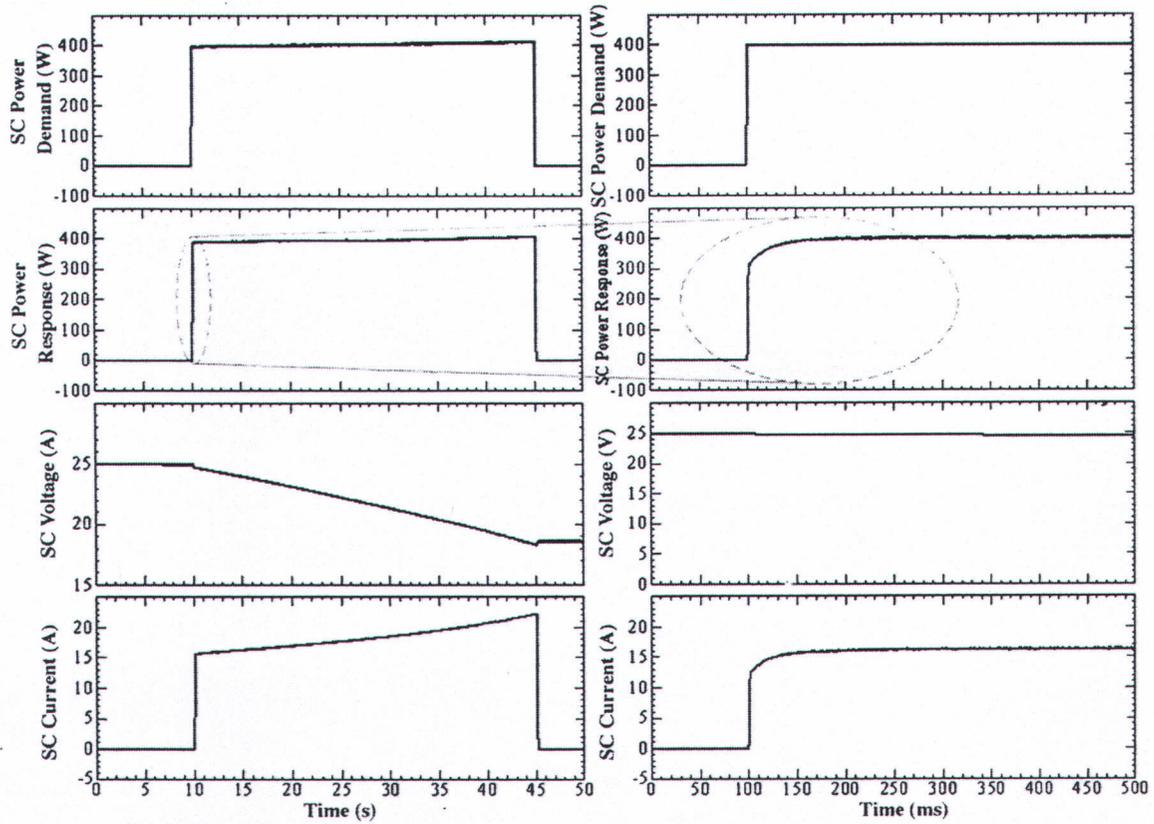


Fig. 8. Dynamic identification of supercapacitor power control loop.

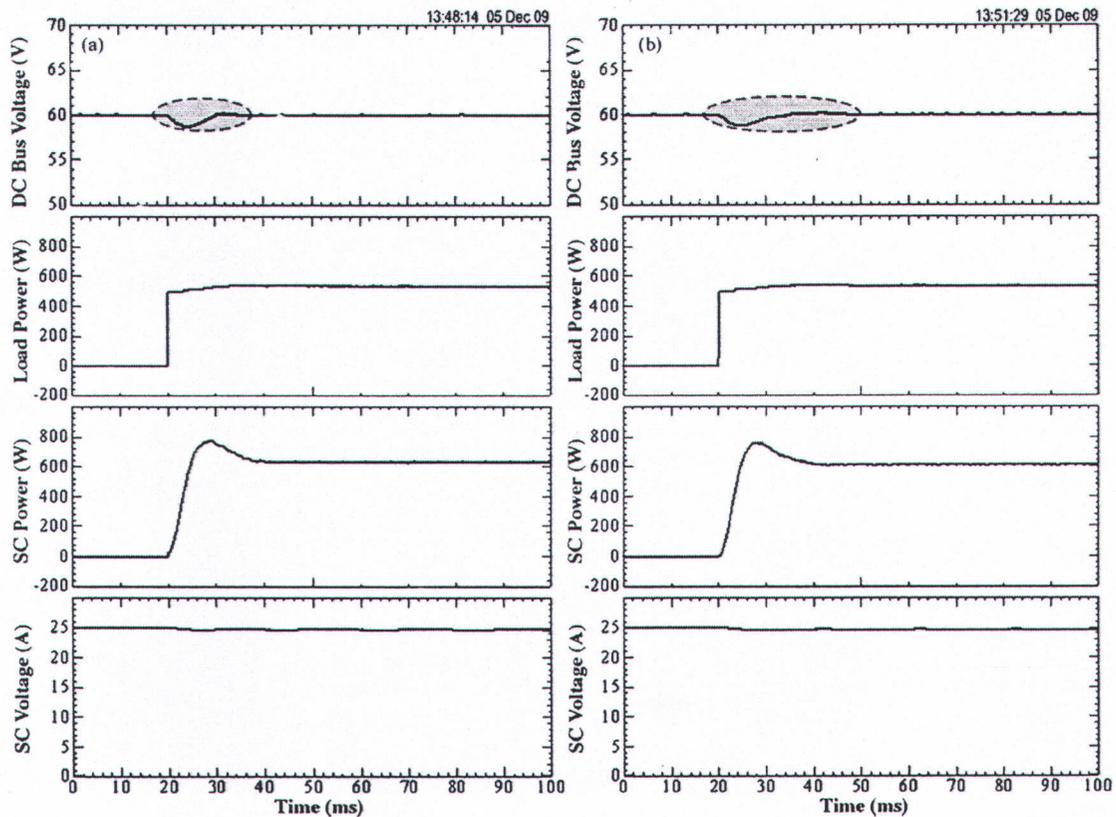


Fig. 9. Comparison of d.c. link stabilization of hybrid energy source during large load step. (a) exact model ( $r_{FC} = 0.14 \Omega$ ,  $r_{Sol} = 0.12 \Omega$ ,  $r_{SC} = 0.10 \Omega$ ) and (b) error model (robustness) ( $r_{FC} = 0 \Omega$ ,  $r_{Sol} = 0 \Omega$ ,  $r_{SC} = 0 \Omega$ ).

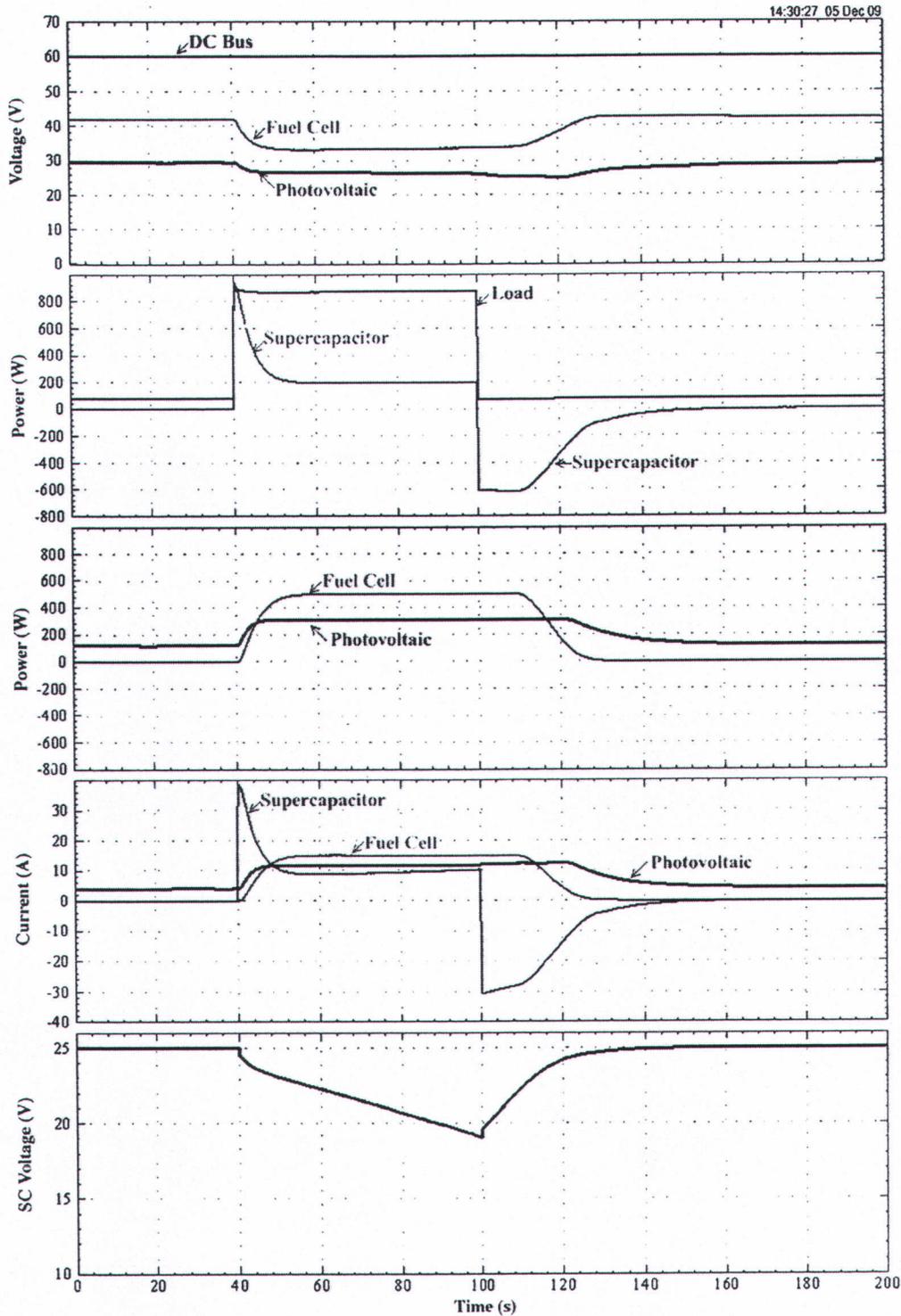


Fig. 10. Hybrid source response during load cycle.

similar to the test bench results in Fig. 10. During the experiment, the FC maximum power was set to 500 W, and the PV maximum power (depending on solar radiation, weather conditions and temperature) was limited by the MPPT. For example, at 15:01:40, the PV maximum power was approximately equal to 180 W; at 15:02:30, the PV maximum power was about 180 W; at 15:03:20, the PV maximum power was around 180 W; and from 15:05:50 to 15:08:20, the PV maximum power was reduced to 0 W, because of the cloudy

conditions. In particular, it was found that the power plant was always energy balanced  $p_{Load}(t) \approx p_{FC}(t) + p_{Sol}(t) + p_{SC}(t)$  by the proposed original control algorithm.

The important variable necessary to balance the energy in this complex system is the d.c.-bus energy or voltage. From the experimental validation, the d.c.-bus voltage is automatically controlled at the constant set-point, i.e.,  $v_{BUS} = 60$  V. This experiment confirms that the energy in the system is well managed. The fuel cell and

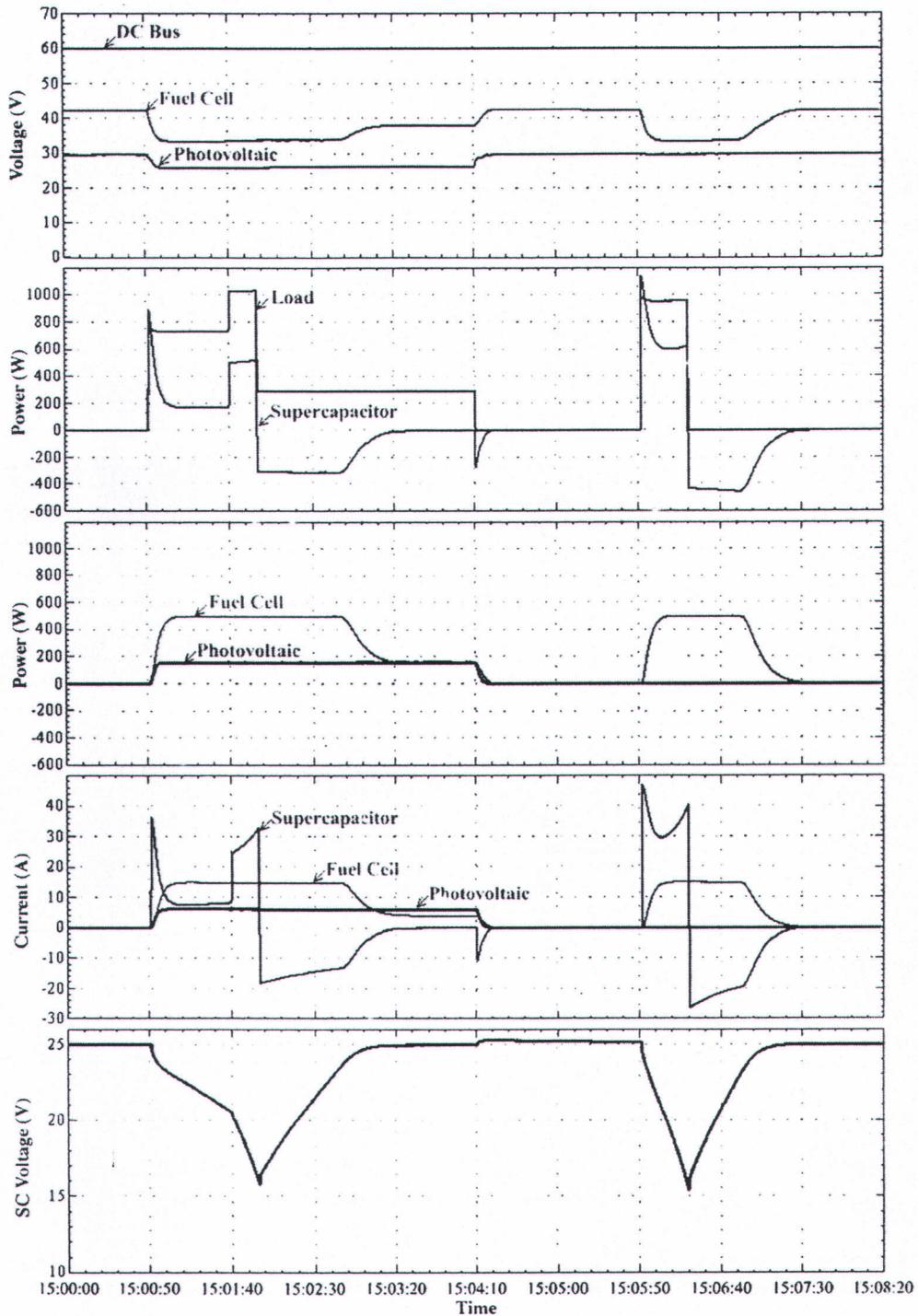


Fig. 11. Hybrid source response during long load cycles.

solar cell powers are limited at their maximum powers, and the fuel cell power dynamics are controlled; as a result, there is no fuel starvation problem and the fuel cell stack lifetime is increased [46–48].

#### 4. Conclusions

Energy management of multi-power sources has been proposed as a solution for a hybrid energy system that uses renewable energy from solar cells, fuel cells and a supercapacitor as an energy stor-

age device. A supercapacitor can advance the load, following the characteristics of the main sources by providing a stronger power response to changes in the system load. During essential steps in the load, the supercapacitor provides the energy balance needed during load transition periods. Adding energy storage to the distributed power systems improves power quality and efficiency.

Experimental verification with a small-scale hybrid test bench (Nexa Ballard fuel cell power generator: 1.2 kW, 46 A; Ekarat Solar Cell power module: 800 W, 31 A; Maxwell supercapacitor storage device: 100 F, 32 V) has demonstrated the excellent performance of

the whole system, and has validated the proposed energy management principle.

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### References

- [1] R. Toonssen, N. Woudstra, A.H.M. Verkooijen, *J. Power Sources* 194 (October (1)) (2009) 456–466.
- [2] K. Rajashekar, J. Grieve, D. Daggett, *IEEE Ind. Appl. Mag.* 14 (July–August (4)) (2008) 54–60.
- [3] N.W. Miller, D. Guru, K. Clark, *IEEE Ind. Appl. Mag.* 14 (March–April (4)) (2009) 54–61.
- [4] A. Bergen, L. Pitt, A. Rowe, P. Wild, N. Djilali, *J. Power Sources* 186 (2009) 158–166.
- [5] G.S. Aglietti, S. Redi, A.R. Tatnall, T. Markvart, *IEEE Trans. Energy Convers.* 24 (June (2)) (2009) 442–451.
- [6] H. Patel, V. Agarwal, *IEEE Trans. Energy Convers.* 24 (March (1)) (2009) 256–263.
- [7] J.R. Salgado, M.A.D. Aguilar, *J. Power Sources* 186 (2009) 455–463.
- [8] J.P. Mock, S.A. Schmid, *J. Power Sources* 190 (2009) 133–140.
- [9] P. Thounthong, B. Davat, S. Raël, P. Sethakul, *IEEE Ind. Appl. Mag.* 15 (July–August (4)) (2009) 52–59.
- [10] P. Corbo, F. Migliardini, O. Veneri, *J. Power Sources* 181 (July) (2008) 363–370.
- [11] M. Kolhe, *IEEE Trans. Energy Convers.* 24 (June (2)) (2009) 511–519.
- [12] T. Senjyu, M. Datta, A. Yona, C.H. Kim, *IEEE Trans. Energy Convers.* 24 (June (2)) (2009) 520–528.
- [13] A.J. del Real, A. Arce, C. Bordons, *J. Power Sources* 193 (2009) 315–321.
- [14] P. Thounthong, S. Raël, B. Davat, *IEEE Trans. Energy Convers.* 23 (January (1)) (2008) 148–155.
- [15] N. Kakimoto, H. Satoh, S. Takayama, K. Nakamura, *IEEE Trans. Energy Convers.* 24 (June (2)) (2009) 465–473.
- [16] A. Cooper, J. Furakawa, L. Lam, M. Kellaway, *J. Power Sources* 188 (2009) 642–649.
- [17] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat, M. Hinaje, *IEEE Trans. Veh. Technol.* 58 (8) (Oct. 2009) 3892–3904.
- [18] E. Schaltz, A. Khaligh, P.O. Rasmussen, *IEEE Trans. Veh. Technol.* 58 (8) (Oct. 2009) 3882–3891.
- [19] J. Bernard, S. Delprat, F.N. Büchi, T.M. Guerra, *IEEE Trans. Veh. Technol.* 58 (September (7)) (2009) 3168–3176.
- [20] J. Bauman, M. Kazerani, *IEEE Trans. Veh. Technol.* 58 (September (7)) (2009) 3186–3197.
- [21] P. Thounthong, S. Raël, B. Davat, *IEEE Trans. Ind. Electron.* 54 (December (6)) (2007) 3225–3233.
- [22] S.J. Chiang, H.J. Shieh, M.C. Chen, *IEEE Trans. Ind. Electron.* 56 (November (11)) (2009) 4344–4353.
- [23] A.F. Segura, E. Durán, J.M. Andújar, *J. Power Sources* 193 (2009) 276–284.
- [24] M. Ferraro, F. Sergi, G. Brunaccini, G. Dispenza, L. Andaloro, V. Antonucci, *J. Power Sources* 193 (2009) 342–348.
- [25] A.E. Auld, J. Brouwer, K.M. Smedley, S. Samuelsen, *IEEE Trans. Energy Convers.* 24 (September (3)) (2009) 617–625.
- [26] P. Thounthong, S. Raël, *IEEE Ind. Electron. Mag.* 3 (September (3)) (2009) 25–37.
- [27] Y. Lembeye, V.D. Bang, G. Lefèvre, J.P. Ferrieux, *IEEE Trans. Energy Convers.* 24 (March (1)) (2009) 203–210.
- [28] S.Y. Choe, J.W. Ahn, J.G. Lee, S.H. Baek, *IEEE Trans. Energy Convers.* 23 (June (2)) (2008) 669–680.
- [29] P. Thounthong, B. Davat, S. Raël, P. Sethakul, *IEEE Ind. Electron. Mag.* 3 (March (1)) (2009) 32–46.
- [30] S.M. Muyeen, R. Takahashi, T. Murata, J. Tamura, *IEEE Trans. Energy Convers.* 24 (September (3)) (2009) 740–749.
- [31] D. Feroldi, M. Serra, J. Riera, *J. Power Sources* 190 (2009) 387–401.
- [32] A. Payman, S. Pierfederici, F. Meibody-Tabar, *Energy Convers. Manage.* 49 (June (6)) (2008) 1637–1644.
- [33] P. Thounthong, S. Raël, B. Davat, *IEEE Trans. Energy Convers.* 24 (March (1)) (2009) 247–255.
- [34] P. Thounthong, S. Raël, B. Davat, *J. Power Sources* 193 (August (1)) (2009) 376–385.
- [35] R. Nozu, M. Iizuka, M. Nakanishi, M. Kotani, *J. Power Sources* 186 (2009) 570–579.
- [36] M.A. Danzer, J. Wilhelm, H. Aschemann, E.P. Hofer, *J. Power Sources* 176 (2008) 515–522.
- [37] H. Aschemann, D. Schindele, *IEEE Trans. Ind. Electron.* 55 (November (11)) (2008) 3855–3864.
- [38] A. Gensior, H. Sira-Ramirez, J. Rudolph, H. Güldner, *IEEE Trans. Ind. Electron.* 56 (February (2)) (2009) 360–370.
- [39] M. Fliess, J. Lévine, Ph. Martin, P. Rouchon, *Int. J. Control.* 61 (6) (1995) 1327–1361.
- [40] M. Fliess, J. Lévine, Ph. Martin, P. Rouchon, *IEEE Trans. Automat. Control.* 44 (May (5)) (1999) 922–937.
- [41] C.P. Mudannayake, M.F. Rahman, *IEEE Ind. Appl. Mag.* 15 (July–August (4)) (2009) 14–25.
- [42] S. Lalouni, D. Rekioua, T. Rekioua, E. Matagne, *J. Power Sources* 193 (2009) 899–907.
- [43] G. Carannante, C. Fraddanno, M. Pagano, L. Piegari, *IEEE Trans. Ind. Electron.* 56 (November (11)) (2009) 4374–4380.
- [44] N. Femia, G. Petrone, G. Spagnuolo, M. Vitelli, *IEEE Trans. Ind. Electron.* 56 (November (11)) (2009) 4473–4482.
- [45] D.J. Perreault, J.G. Kassakian, *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.* 44 (August (8)) (1997) 728–734.
- [46] N. Yousfi-Steiner, Ph. Moçotéguy, D. Candusso, D. Hissel, *J. Power Sources* 194 (October (1)) (2009) 130–145.
- [47] J. Hasikos, H. Sarimveis, P.L. Zervas, N.C. Markatos, *J. Power Sources* 193 (August (1)) (2009) 258–268.
- [48] F. Ettingshausen, J. Kleemann, M. Michel, M. Quintus, H. Fuess, C. Roth, *J. Power Sources* 194 (December (2)) (2009) 899–907.

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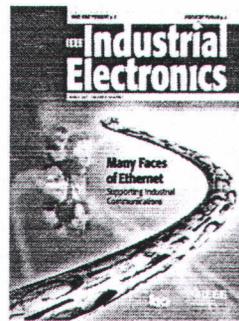
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# Fuel Cell High-Power Applications

*An Overview  
of Power  
Converters  
for a Clean  
Energy  
Conversion  
Technology*

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PHATIPHAT THOUNTHONG,  
BERNARD DAVAT, STÉPHANE RAËL,  
and PANARIT SETHAKUL

**E**nergy consumption plays an important role in our modern civilization and daily life, which is heavily dependent on burning fossil fuels. The increasing threat of the fast depletion of resources such as petroleum, coal, and natural gas forces people to seek regenerative energy sources, such as solar, wind, geothermal, and hydroelectric energies. Another way of saving valuable natural resources and solving the environmental problem is to develop cleaner and more efficient energy conversion devices. In recent years, fuel cell (FC) research and development have received much attention for their higher energy conversion efficiency and lower or nongreenhouse-gas emissions than thermal engines in the processes of converting fuel into usable energies [1]–[3]. The power and energy efficiency of an FC is highly dependent on thermodynamics, electrode kinetics, and reactant mass transfer, as well as materials and components for assembling the FC. These factors have been addressed throughout the FC history and are now still the major challenges for FC research and development [4]–[6].

In industry, United Technologies Corporation (UTC) Fuel Cells is involved in FC systems for space and defense applications. UTC Fuel Cells activity began in 1958 and led to the development of the first practical FC application used to generate electrical power and potable water for the Apollo space missions. Since 1966, all of the more than 100 manned U.S. space flights, including the Space Shuttle, have operated with FCs supplied by UTC companies. In 1991, UTC Fuel Cells manufactured its first PureCell 200 power plant, the world's first and only commercial FC power. The PureCell 200 FC produces 200-kW of electricity and 700,000 BTUs of heat. The unit can be powered by natural gas, propane, butane, hydrogen, naphtha, or gases from waste. Since their first flight in 1981, UTC Fuel Cells power plants have provided electric power for more than 100 shuttle missions. They shipped a 50-kW hydrogen-air

FC power plant to the U.S. Department of Energy (DOE) and the Ford Motor Company. In 1998, UTC Fuel Cells delivered a 100-kW methanol power plant, with 40% efficiency, to Nova Bus for installation in a 40-ft, hybrid drive electric bus under a DOE/Georgetown University contract [7], [8].

General Motors is involved in the development of FCs for stationary power as well as the more obvious automotive markets [9]–[11]. In February 2004, they began the first phase of installation operations in Texas at Dow Chemical Company, the largest facility in the world. These FC systems are used to generate 35 MW of electricity [12].

## **Fuel cells produce dc voltage outputs, and they are always connected to electric power networks through power conditioning units such as dc/dc and dc/ac converters.**

Axane (France) is also working on FC technology. Three markets that are likely to provide large commercial outlets [13], [14] are:

- portable multiapplication generators (500 W–10 kW)
- stationary applications (more than 10 kW)
- mobile applications for small hybrid vehicles (5–20 kW).

FCs produce dc voltage outputs, and they are always connected to electric power networks through power conditioning units such as dc/dc and dc/ac converters. Power conversion and control functions form the basis of what has come to be known as the field of power electronics. In recent years, power electronics technology has been spurred by needs for efficient control of industrial applications and the development of more reliable lightweight switching power supplies for a sophisticated system. This article reviews the current research of power electronic converters for FC high-power applications.

### **FC Technology**

An FC is a device that converts the chemical energy of a fuel directly to electrical energy. Its concept was pro-

posed approximately 170 years ago when William Robert Grove conceived the first FC in 1839, which produced water and electricity by supplying hydrogen and oxygen into a sulfuric acid bath in the presence of porous platinum electrodes [1]. The process by which this is done is very similar to the electrochemical process by which a battery generates power; at one electrode, a fuel such as hydrogen is oxidized, and at the other electrode an oxidant such as oxygen is reduced. The reactions exchange ions through a solid or liquid electrolyte and electrons through an external circuit, as shown in Figure 1 [15], [16].

The theoretical value of a single cell voltage of FC is 1.23 V. It is never reached even at no load. At the rated current, the voltage of an elementary cell is about 0.6–0.7 V [17]–[19]. Therefore, an FC is always an assembly of elementary cells that constitute a stack, as Figure 2 depicts.

There are many different types of FCs, with the principal differences between them being the type of electrolyte and/or the type of fuel that they use. For instance, both the phosphoric acid FC (PAFC) and the molten carbonate FC (MCFC) have a liquid electrolyte, whereas a solid oxide FC (SOFC) has a solid, ceramic electrolyte [20]–[22]. A proton exchange or polymer electrolyte membrane FC (PEMFC) and a direct methanol FC (DMFC) may have the same solid polymer electrolyte, but the DMFC uses liquid methanol for fuel whereas the PEMFC uses gaseous hydrogen [23], [24].

Currently, there are three general areas of application for FC technology: portable power, distributed power, and transportation. For each application, it is generally found that one type of FC is better suited than the others to satisfy the requirements of

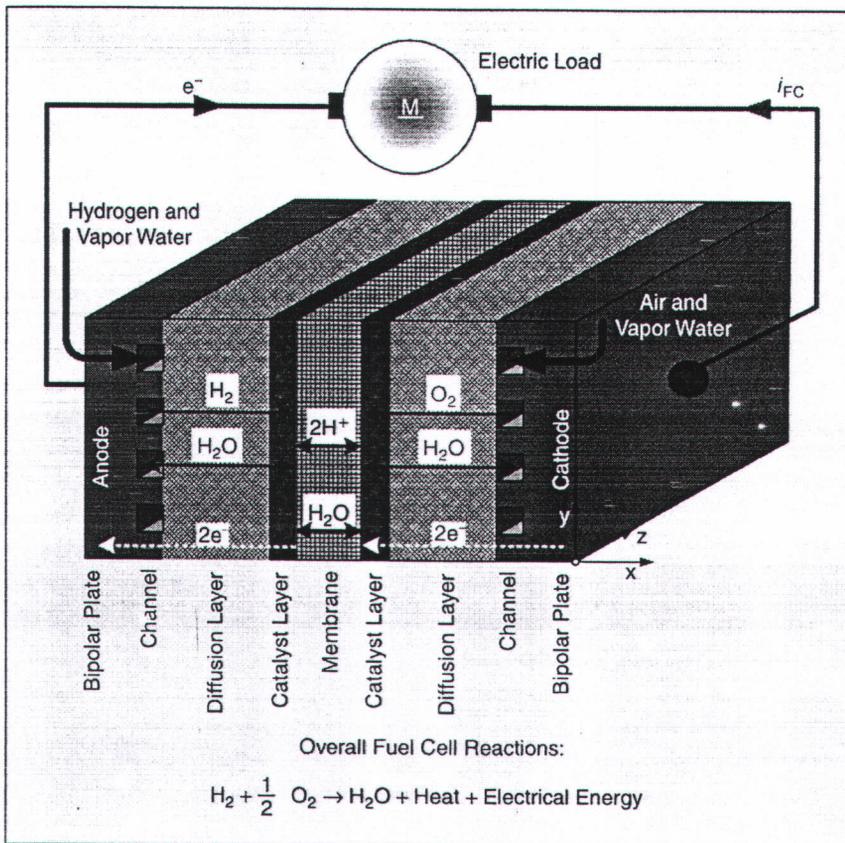


FIGURE 1 – Different layers of an elementary cell of PEMFC.

the application. The DMFCs are attractive for several applications in view of their lower weight and volume. The DMFCs are increasingly being developed to replace or support batteries, mainly for the high energy density of methanol. The DMFCs are promising candidates as portable power sources because they do not require any fuel processing and operate at low temperatures (30–60 °C) [25]–[27]. The SOFC, because of its high power density and high grade waste heat that may be used in cogeneration applications, is a front-runner in distributed power applications at the industrial level [28]–[31]. The PEMFC has many of the qualities required of an automotive power system including relatively low operating temperature, high power density, and rapid startup [32]–[34]. In addition, PEMFC may also be used in residential and commercial power systems [35].

An FC stack requires fuel, oxidant, and coolant in order to

operate. The composition, pressure, and flow rate of each of these streams must be regulated. In addition, the gases must be humidified and the coolant temperature must be controlled. To achieve this, the FC stack must be surrounded by a fuel system, fuel delivery system, air system, stack cooling system, and humidification system. Once operating, the output power generated by the FCs must be conditioned

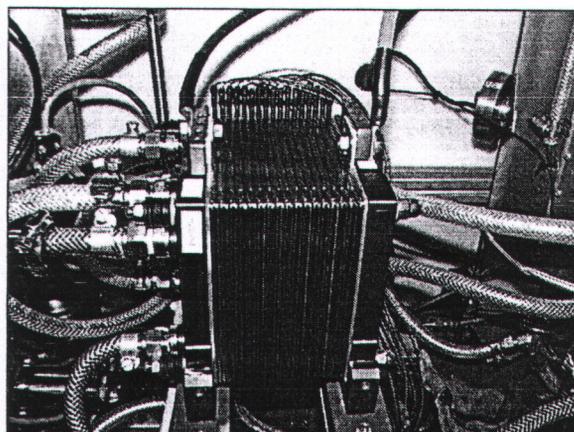


FIGURE 2 – An PEMFC (16 cells, 500 W, 50 A, and around 11 V) manufactured by the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) Company. It is being functioned at the GREEN laboratory.

and absorbed by a load (converter). Suitable alarms must shut down the process if unsafe operating conditions occur, and a cell voltage monitoring system must monitor FC stack performance. These functions are performed by electrical control systems. As an example, Figure 3 shows a simplified diagram of the PEMFC system. When an FC operates, its fuel (hydrogen and air) flows are controlled by an FC controller, which receives current demand. This current demand is the FC current reference  $i_{FCREF}$  (see Figure 3) coming from the energy management controller. The fuel flows must be adjusted to match the reactant delivery rate to the usage rate by the FC controller [36], [37].

### FC Characteristics

As mentioned earlier, an FC power source is always connected to the dc bus by a step-up converter. Switching characteristics of the PEMFC (500 W, 40 A) at steady-state when connecting with a boost converter are presented in Figure 4. It can be seen that the PEMFC contains a complex impedance component, which it is not purely resistive at a high switching frequency of 25 kHz [36].

Thounthong et al. [38] (who worked with a 500-W PEMFC system by ZSW Company), Corrêa et al. [39], [40] (who worked with a 500-W Ballard and 500-W Avista PEMFC system), and Zhu et al. [41] (who worked with a 500-W PEMFC system) have demonstrated

that the electrical response time of an FC is generally fast, being mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. On the other hand, because an FC system is composed of many mechanical devices, the whole FC system has slow transient response and slow output power ramping [42], [43].

For clarity about the FC dynamics, Figure 5 illustrates a Nexa PEMFC system (1.2 kW, 46 A), and Figure 6 depicts the FC voltage response to a current

demand of the Nexa PEMFC stack. The tests operate in two different ways: current step and controlled current slope of  $2 \text{ A}\cdot\text{s}^{-1}$ . One can scrutinize the voltage drop in Figure 6(a), compared to Figure 6(b), because fuel flows (particularly the delay of air flow) have difficulties following the current step. This characteristic is called fuel starvation phenomenon [1], [44]–[47]. The same kind of FC dynamic responses can be seen in [48]. This condition of operation is evidently dangerous for the FC stack, as already demonstrated by Taniguchi et al. [49]. To utilize the FC in dynamic applications, its current or power slope must be limited, for example,  $4 \text{ A}\cdot\text{s}^{-1}$  for a PEMFC (0.5 kW, 12.5 V) [50]; a  $2.5 \text{ kW}\cdot\text{s}^{-1}$  for a PEMFC (40 kW, 70 V) [51]; and  $500 \text{ W}\cdot\text{s}^{-1}$  for a PEMFC (2.5 kW, 22 V) [52].

Therefore, the constraints to operate an FC are as follows:

- 1) The FC power or current must be kept within an interval (rated value, minimum value or zero).
- 2) The FC current must be controlled as a unidirectional current.
- 3) The FC current slope must be limited to a maximum absolute value (for example,  $4 \text{ A}\cdot\text{s}^{-1}$  [53]), to prevent an FC stack from the fuel starvation phenomenon.
- 4) Switching frequency of the FC current must be greater than 1.25 kHz, and the FC ripple current must be lower than around 5% of rated value, to ensure minor impact to the FC conditions [54], [55].

### FC Power Conditioning

The power conditioning system provides regulated dc or ac power appropriate for the application. It is the major component of an FC distributed system. The output of the FC is an unregulated dc voltage (see Figure 6), and it needs to be conditioned in order to be of practical use. The power conditioner section converts the FC power to usable power for different applications. The power conditioning unit also controls electricity's frequency and maintains harmonics to an acceptable level. The purpose of conditioners is to adapt the electrical current from FC to suit the electrical

needs of the application. FC operates giving direct current and at a low voltage; thereby, the step-up (boost)

converter (dc/dc converter, named here FC converter) is always selected to adapt the low dc voltage delivered

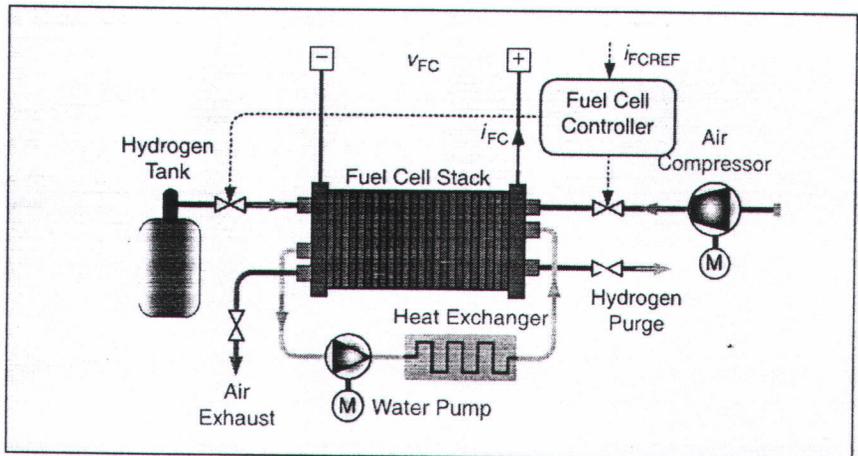


FIGURE 3 – Simplified diagram of the PEMFC system.  $V_{FC}$ ,  $i_{FC}$ , and  $i_{FCREF}$  are the FC voltage, current, and current demand, respectively.

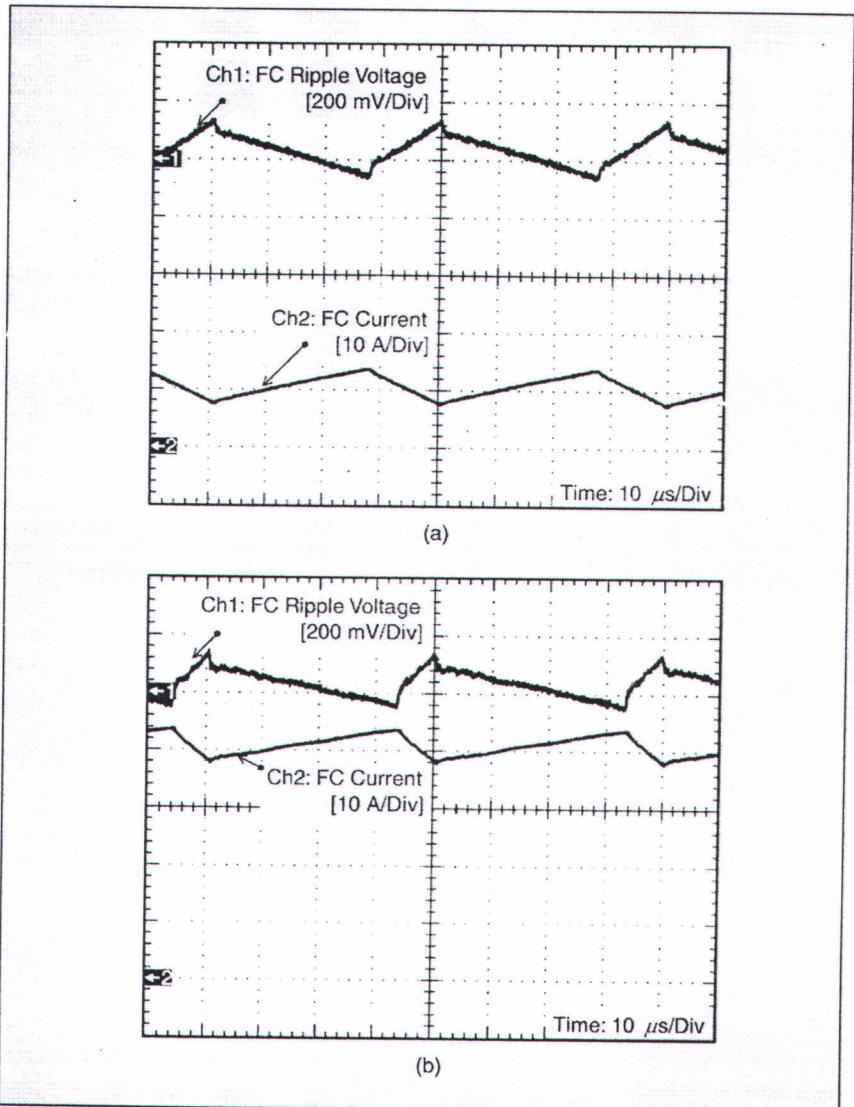


FIGURE 4– Switching characteristics of a 500 W PEMFC of 25 kHz at the FC current supply of (a) 10 A and (b) 40 A (rated current).

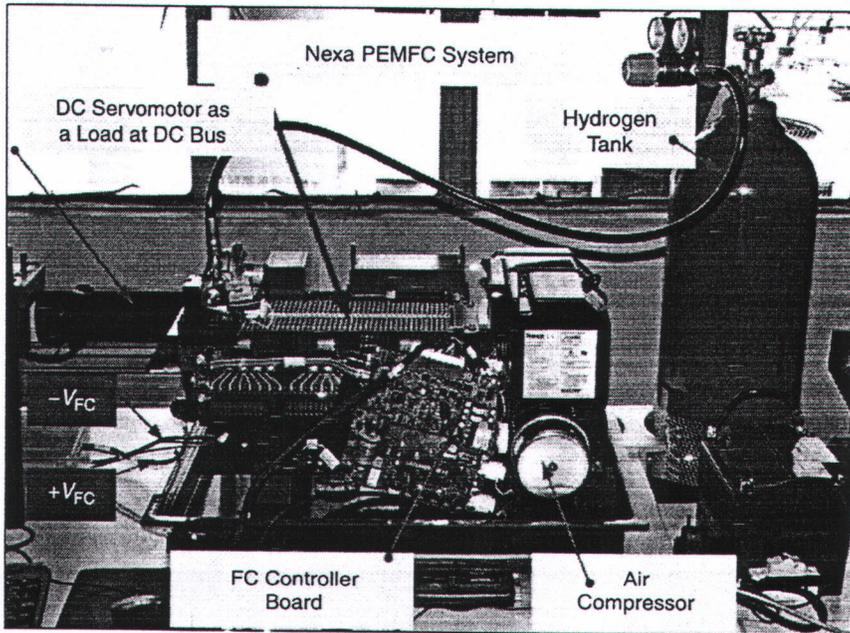


FIGURE 5 – A Nexa PEMFC (1.2 kW, 46 A). It is being functioned at the TFII laboratory.

by the FC to the utility dc bus followed by an inverter (Figure 7) [56]. In general, the load for the boost stage is a filter and the inverter system.

The inverter is used for the interfacing of the FC system to the power grid to provide the grid with voltage/current with proper frequency phase and magnitude where the input for the inverter comes from the boost converter stage and the inverter (with the filter) becomes the load for the boost converter. The power conditioner is also used for the grid connection of the FC. An electrical power-generating system that uses FC as the primary source of electricity generation and is intended to operate synchronously, and in parallel with the electric utility network is a grid-connected FC system [57], [58]. Such systems may also include storage devices and other generating sources and may operate on site loads independent of the utility network during outages.

To employ the FC as a main power source in dynamic applications (such as an electric vehicle [59]–[61] and railway vehicle [62]–[64]), the electrical system must have at least an auxiliary power source (storage device) to improve the dynamic performances of the whole system, when electrical loads at a dc bus demand high power in a short time (for example, vehicle acceleration and deceleration), as portrayed in Figure 8. Moreover, one can take advantage of this auxiliary power source to achieve an actual hybrid source to disassociate mean power sizing from peak transient power sizing, the aim being a reduction in volume and weight, and in the case of FCs used as main energy source, the possibility of regenerative braking [38], [65]. For example, some authors have described the study of the FC/battery hybrid power source [66]–[70] and the FC/supercapacitor hybrid power source [71]–[73].

For the past ten years, much research has been conducted on the utilizations of FCs in high power applications. Today, the required FC power is in the range of 1 kW to 2 MW:

- 1–2 kW for unmanned aircrafts [74]
- and 40–700 kW for manned aircraft [75]–[78]

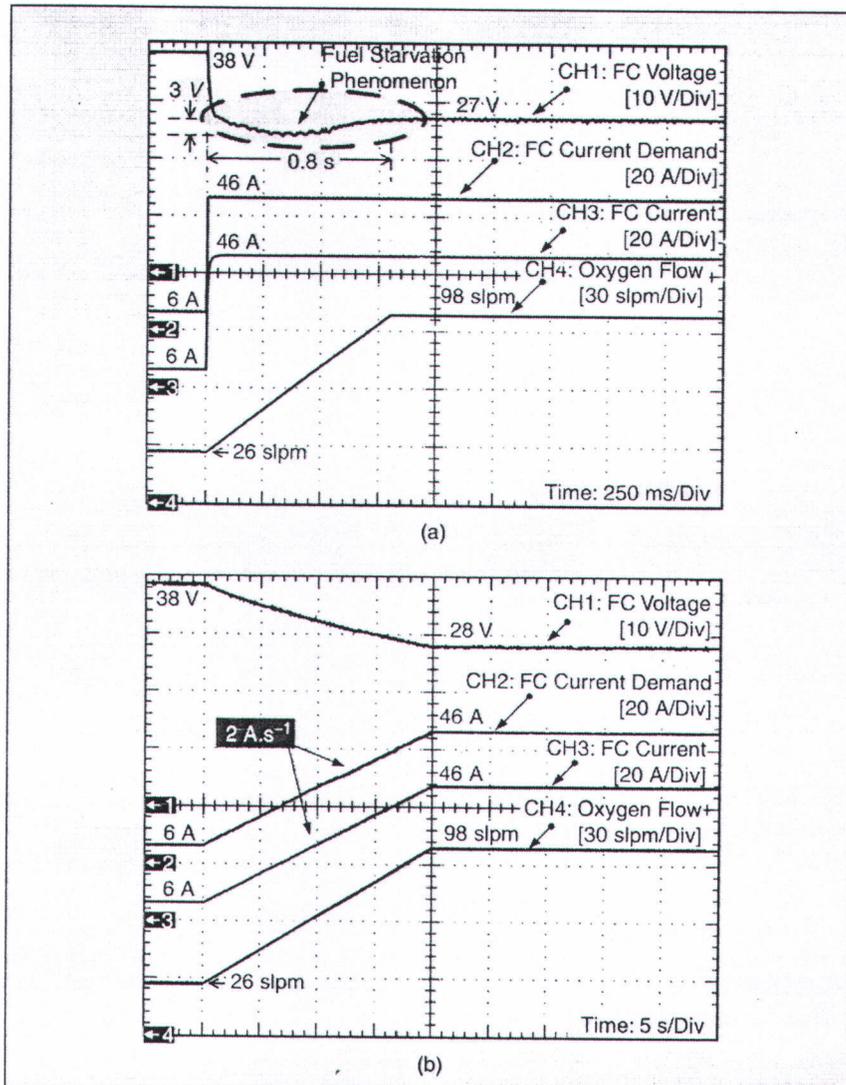


FIGURE 6 – FC dynamic characteristics to (a) current step and (b) controlled current slope of  $2 \text{ A}\cdot\text{s}^{-1}$ .

- 50–100 kW for urban cars [9], [33], [79]–[85]
- 100–200 kW for buses and light trams [7], [86]–[88]
- 600 kW–1 MW for tramways and locomotives [62]–[64], [89]–[92] (for example four motors of 180-kW peak are installed on a tramway, two motors per boggy. The total power installed is 800 kW)
- 480 kW–2 MW for distributed generation systems (grid parallel connection) [8], [93].

To increase the power and voltage levels, several configurations for the FC association can be envisaged as depicted in Figure 9 [93]–[98]. For association of the converter inputs, we can connect several FC in series and then connect them to a converter or each FC to a converter. The FC parallel connection is currently complicated because of complexity of controlling the output power distribution in each FC. For association of converter outputs, the output of a converter can be connected in series for a high output voltage or in parallel for a low output voltage.

### FC Power Converter

Different power converter topologies can be used for the power electronic interface between the FC and the utility dc bus. For the dc link

**A large research effort is underway to develop the FC for applications ranging from small portable electronic devices to automotive transport, as well as residential combined heat and power supplies.**

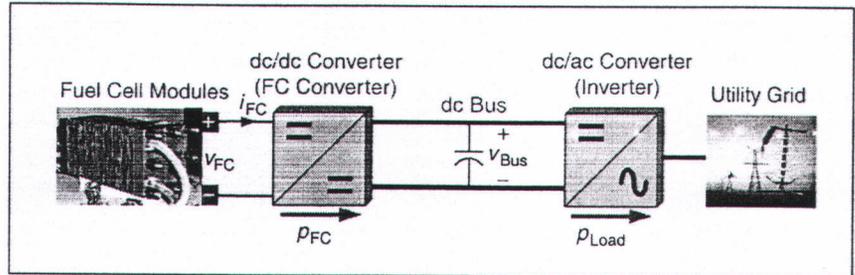


FIGURE 7 – FC power system.

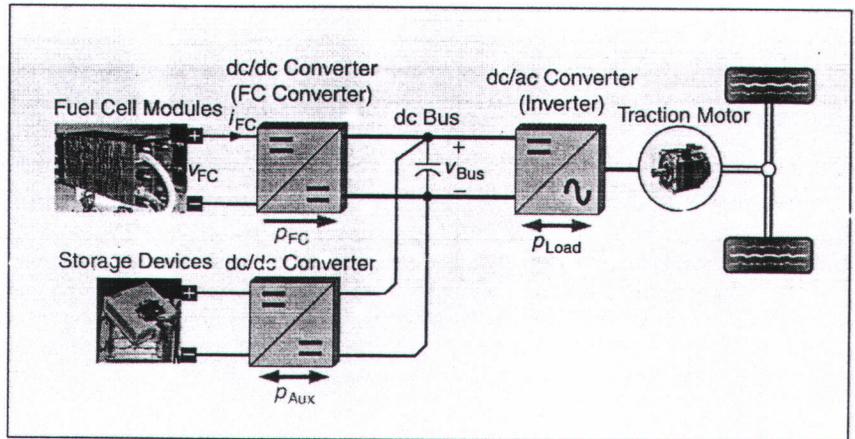


FIGURE 8 – Fuel cell powered vehicle.

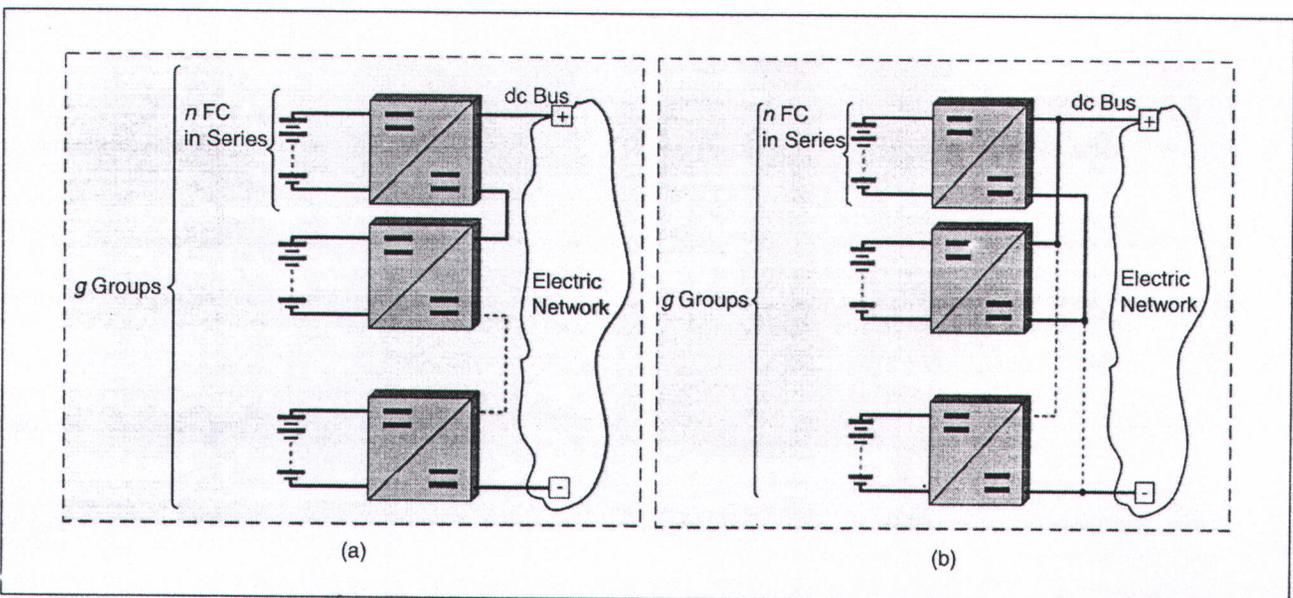


FIGURE 9 – Modular stack FC architectures connected to the dc bus: (a) output connected in series and (b) output connected parallel.  $n$ : number of FC in series in each group,  $g$ : number of FC-converter groups.

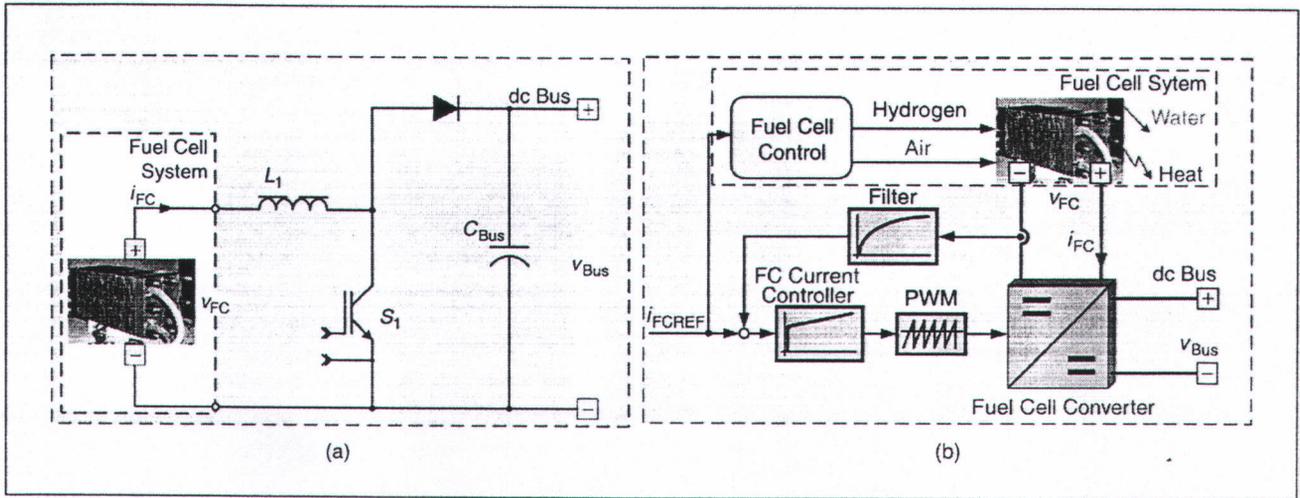


FIGURE 10 – Classical fuel cell boost converter: (a) power circuit and (b) FC current regulation loop.

voltage level, it is depending on its applications:

- 270 V or 350 V for the standard on the all-electric aircraft [78]
- 48 V [99], 120 V [100], or 400–480 V [30], [93], [101] for stand-alone or parallel grid connections
- 42 V (PowerNet) a new standard voltage for automobile systems [34], [102], [103]

- 270–540 V for electric (FC) vehicles [60], [65], [82]
- 350 V (transit bus systems) to 750 V (tramway and locomotive systems) [7], [63], [64], [87], [89]–[92], [104].

Basically, low-voltage, high-current structures are needed because of the FC electrical characteristics. A classical boost converter is often selected as an FC converter [38], [93], [99]–[101],

[105]–[107], because it can be operated in the current control mode in a continuous condition mode, as portrayed in Figure 10. Then, one does not need a blocking diode and passive filter between an FC and a converter. Based on the load conditions, the boost converter can be commanded to draw a specific amount of current from the FC with a ripple well defined by the frequency, size of the inductor, and duty ratio. The FC boost converter sizes of 0.5 kW [38]; 1 kW [100], [101], [105]; 5 kW [99]; 27 kW [106]; and 50 kW [93] have been studied. However, a classical boost converter will be limited when the power increases or for higher step-up ratios. In that way, the use of paralleling power converters with interleaved technique may offer some better performances.

#### Parallel Power Converter with Interleaved Switching Algorithm

The subject of paralleling power converters was on the sideline of design engineering tasks for decades. Latest efforts in standardization, miniaturization, and the proliferation of high current, low voltage power supplies have directed additional attention to various techniques to parallel power modules. The fundamental difficulty using parallel power processing circuits is to ensure that the load current is properly distributed among the parallel connected power modules. Only then can the design be optimized for the highest

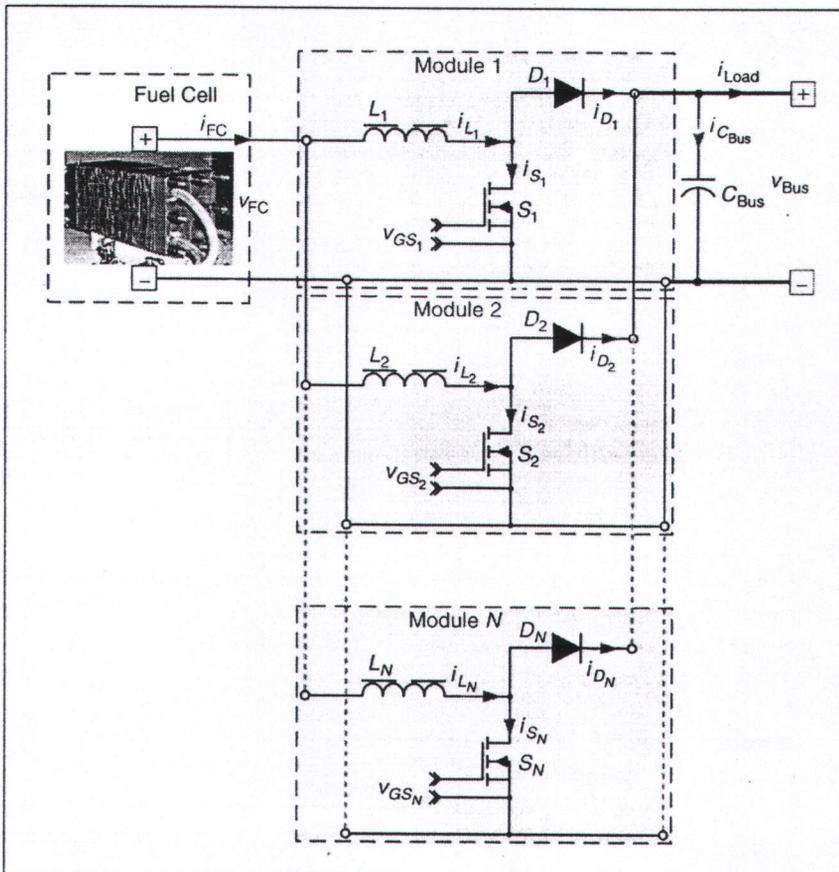


FIGURE 11 – Multiphase paralleled step-up converters for FC high-power applications.

reliability and lowest cost by ensuring equal temperature rise and by minimizing the power rating of the individual components.

The major problems of using a single dc/dc converter connected with FC in high power applications are as follows:

- difficulty of the design of magnetic component: ferrite core and Litz-wire size
- high FC ripple current, which may lead to reduce its stack lifetime.

Therefore, by paralleling converters with interleaving technique, these problems can be avoided [108]–[111]. A high-power dc distributed power system supplied by FC invokes the need to parallel power modules with interleaving technique. Active ripple cancellation methods can yield even higher performance. Today, the active method of interleaving is well known [94], [96], [98]. In the interleaving method, the modules operate at the same switching frequency. Their switching waveforms are displaced in phase over a switching period with respect to one another by  $2\pi/N$  radians, with  $N$  being the number of converters in parallel. It is important to note here that, according to [54] and [55], a high FC current ripple plays an important role in its catalyst lifetime. Especially,

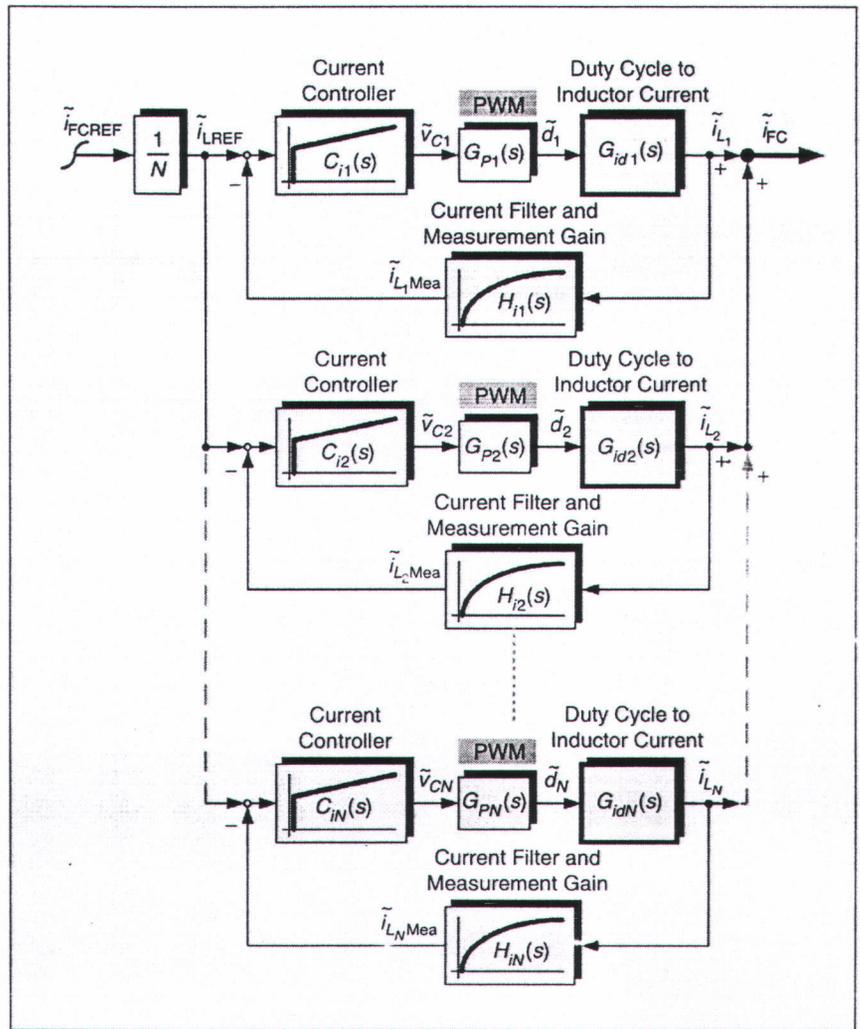


FIGURE 12 – Current sharing technique of  $N$ -phase parallel modules (here, boost converters).

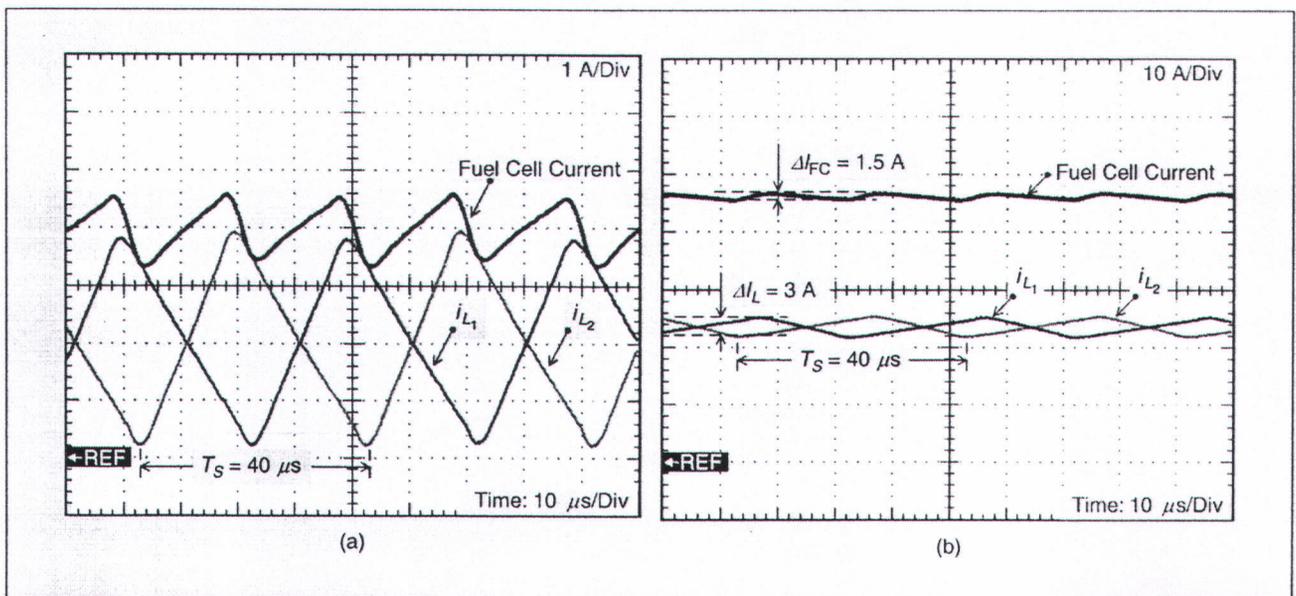


FIGURE 13 – Steady-state waveforms of the two-cell interleaved converter system at an FC current command of (a) 4 A ( $v_{FC} = 35.8$  V) and (b) 46 A rated current ( $v_{FC} = 26.3$  V).

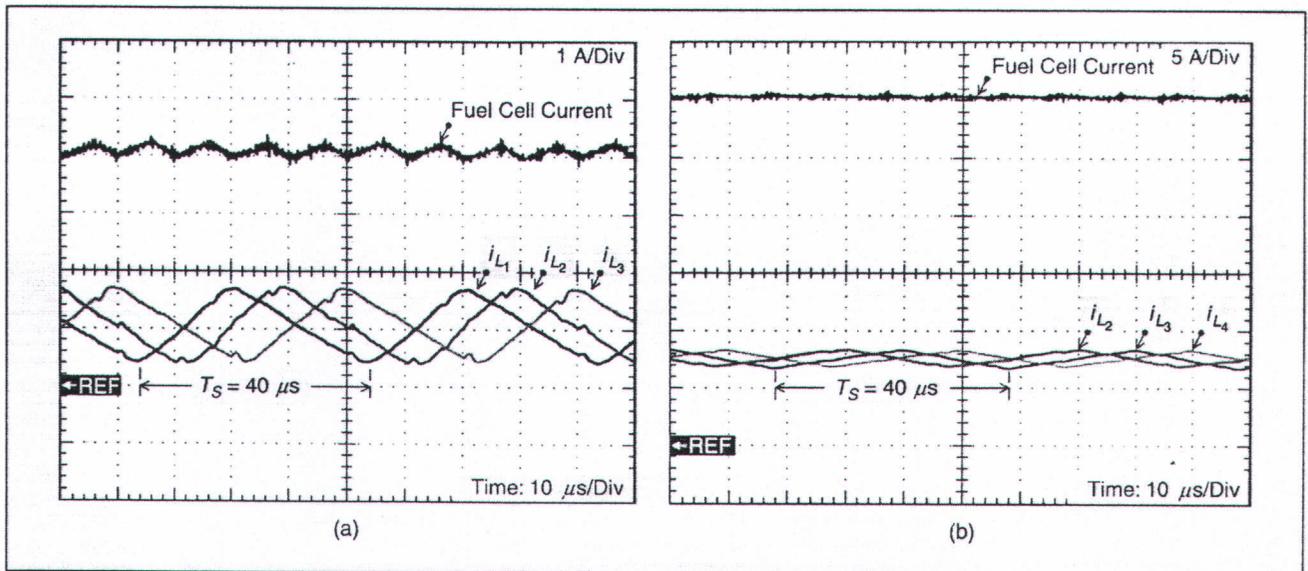


FIGURE 14 – Steady-state waveforms of the four-cell interleaved converter system at an FC current command of (a) 4 A ( $v_{FC} = 35.8$  V) and (b) 30 A ( $v_{FC} = 28.9$  V).

sharp current rise/fall and large magnitude of current ripple should be avoided. The multiphase parallel converters for FC high-power applications are depicted in Figure 11.

The most sophisticated and most accurate current sharing implementations rely on a closed loop negative feedback system, very similar to those control loops used to regulate

the output voltage of a power supply, as portrayed in Figure 12 [112], [113]. To make this approach work, two piec-

tor currents of the modules and the other is the desired amount of FC current reference  $i_{FCREF}$ . Since the goal is to evenly distribute the FC current, the desired FC current is the FC current divided by the number of parallel modules. Therefore the task is two fold; measure the inductor currents and generate the average inductor current set-points.

**There are three general areas of application for FC technology: portable power, distributed power, and transportation.**

es of information must be available in the system. One is the actual induc-

the inductor currents and generate the average inductor current set-points.

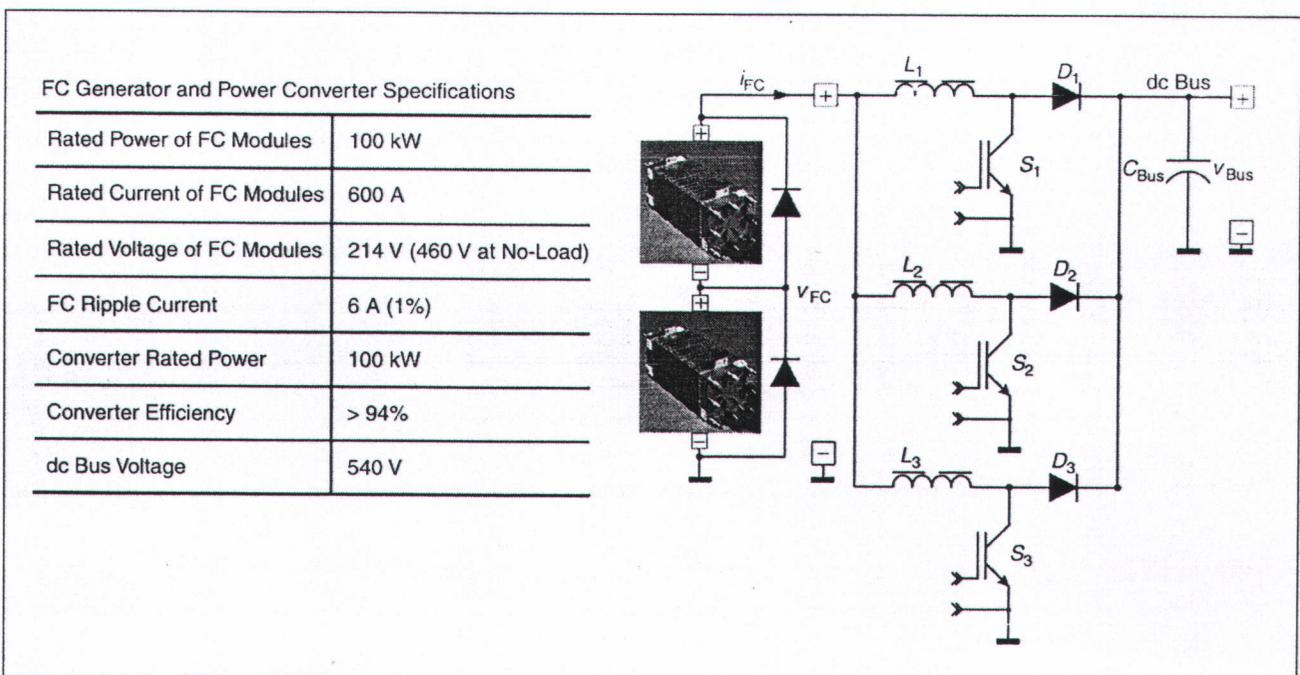


FIGURE 15 – 100-kW FC converter of three-phase interleaved boost converters with two FC modules in series [98].

According to Thounthong et al. [114], [115], who worked with a Ballard Nexa PEMFC unit (1.2-kW, 46-A, see Figure 5), they have already demonstrated the experimental results of the two- and four-phase paralleled boost converters for FC applications. The oscilloscope waveforms in Figures 13 and 14 portray the steady-state characteristics of the interleaved converters at different FC current demands, the load at dc bus being adjusted in order to obtain a constant dc bus voltage of 60 V (here rated value). Figure 13 illustrates the FC current, and the first and the second inductor currents of the two-phase parallel converter at the average FC current reference of 4 A and 46 A (rated current), respectively [114]. Figure 14(a) presents the FC current and the first, second, and third inductor currents of the four-phase parallel converters at the average FC current reference of 4 A. For the last test, Figure 14(b) shows the FC current and the second, third, and fourth inductor currents of the 4-phase parallel converters at the average FC current reference of 30 A [115].

One can observe again that the FC current is the sum of the inductor currents and that the FC ripple current is 1/N the individual inductor ripple currents. Absolutely, the FC ripple current of the four-cell interleaved converter is lower than the two-cell interleaved converter. So, the FC ripple current of

## The PEMFC is well suited to automotive power applications and may be used in residential and commercial power systems.

the four-cell interleaved converter is nearly zero. It means that the FC mean current is close to the FC rms current. In addition, it can be seen the FC ripple frequency is  $N$ -times the switching frequency of 25 kHz.

According to Hwang et al. [116], an FC converter size of 1 kW with four-phase interleaved boost cells had been also presented. For an FC converter size of 150 kW (technical specification:

$V_{FC} = 250\text{--}450\text{ V}$ ,  $V_{Bus} = 548\text{ V}$ , weigh 50 kg) with two-phase interleaved boost converters had been fabricated and tested [117]. Its volume and weight is less than one third of a single phase boost converter, the FC ripple current is less than 10%, and its efficiency is over 97%. According to Vulturescu et al. [98], the design of an FC converter size of 100 kW with three-phase interleaved boost converters with two

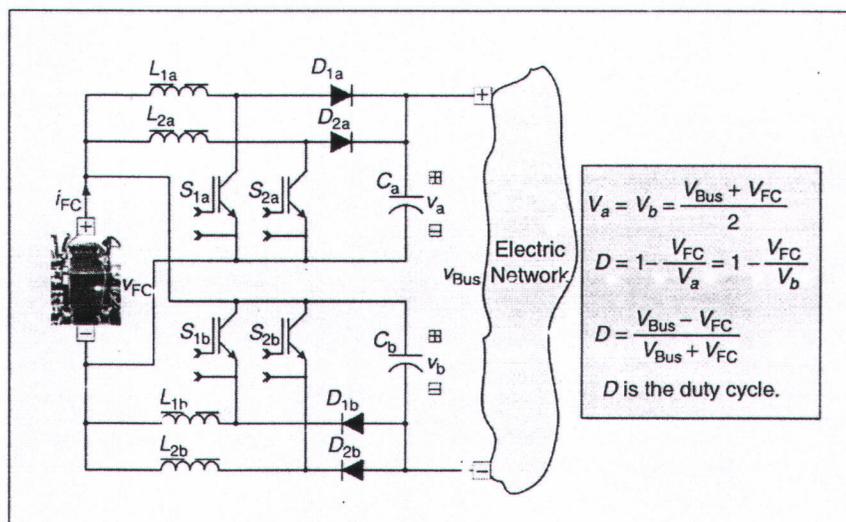


FIGURE 16 – 120-kW two-branches interleaved double dual boost converters [96].

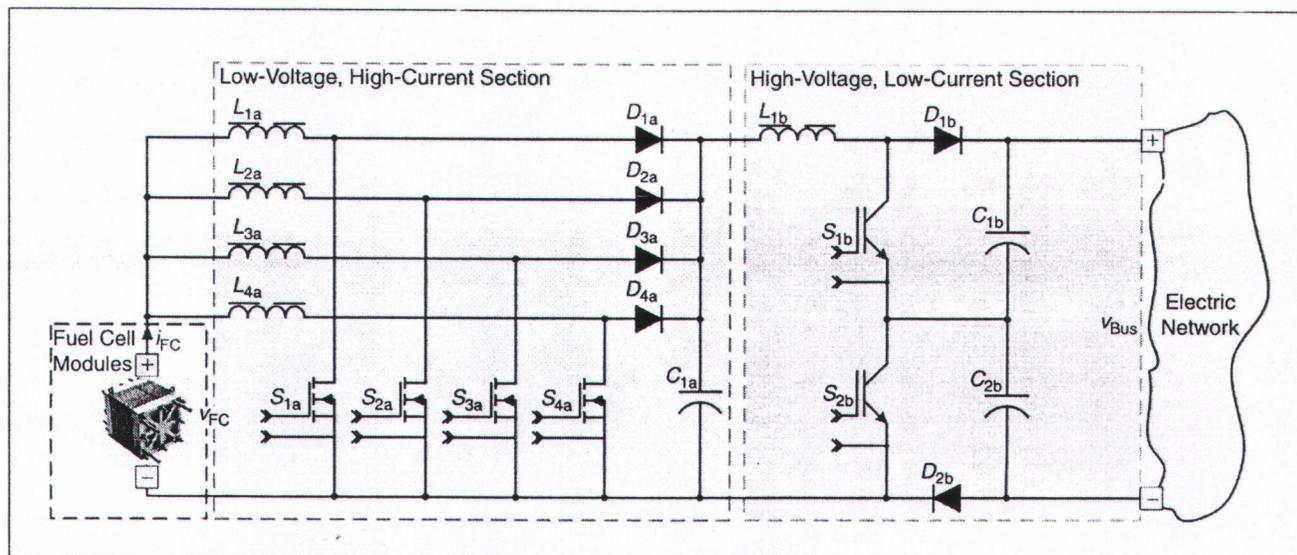


FIGURE 17 – 200-kW cascade-parallel boost converter for the FC power converter.

## FCs hold great promise as a clean energy conversion technology.

FC modules in series has been studied for French urban transportation networks, as depicted in Figure 15. In addition, a three-phase interleaved boost modules based on the commercial standard Lopak5 of insulated gate bipolar transistors (IGBTs) by Asea Brown Boveri Ltd. (ABB) for 250–1,000-kW FC converter at the dc link voltage

of 750 V has been proposed in [118]. For the FC urban car, the 94-kW FC converter with the multiphase interleaved boost converters at the dc link voltage of 320 V had been designed and used in the HydroGen3 FC vehicle of General Motors (GM) Company [119].

To increase the higher voltage conversion ratio, Viet et al. [96] have

proposed the two-branches interleaved double dual (IDD) boost converters for an FC converter: 20–120 kW, as shown in Figure 16. One summarizes that this scheme can boost the FC input voltage from 60–700 V utility dc bus at the FC current of 333 A (20 kW).

Another possibility to increase the voltage conversion ratio of the FC high-power converter is cascade-parallel boost converter, as Figure 17 illustrates. This similar concept has been proposed in [120]–[122]. One might suppose that this power converter can

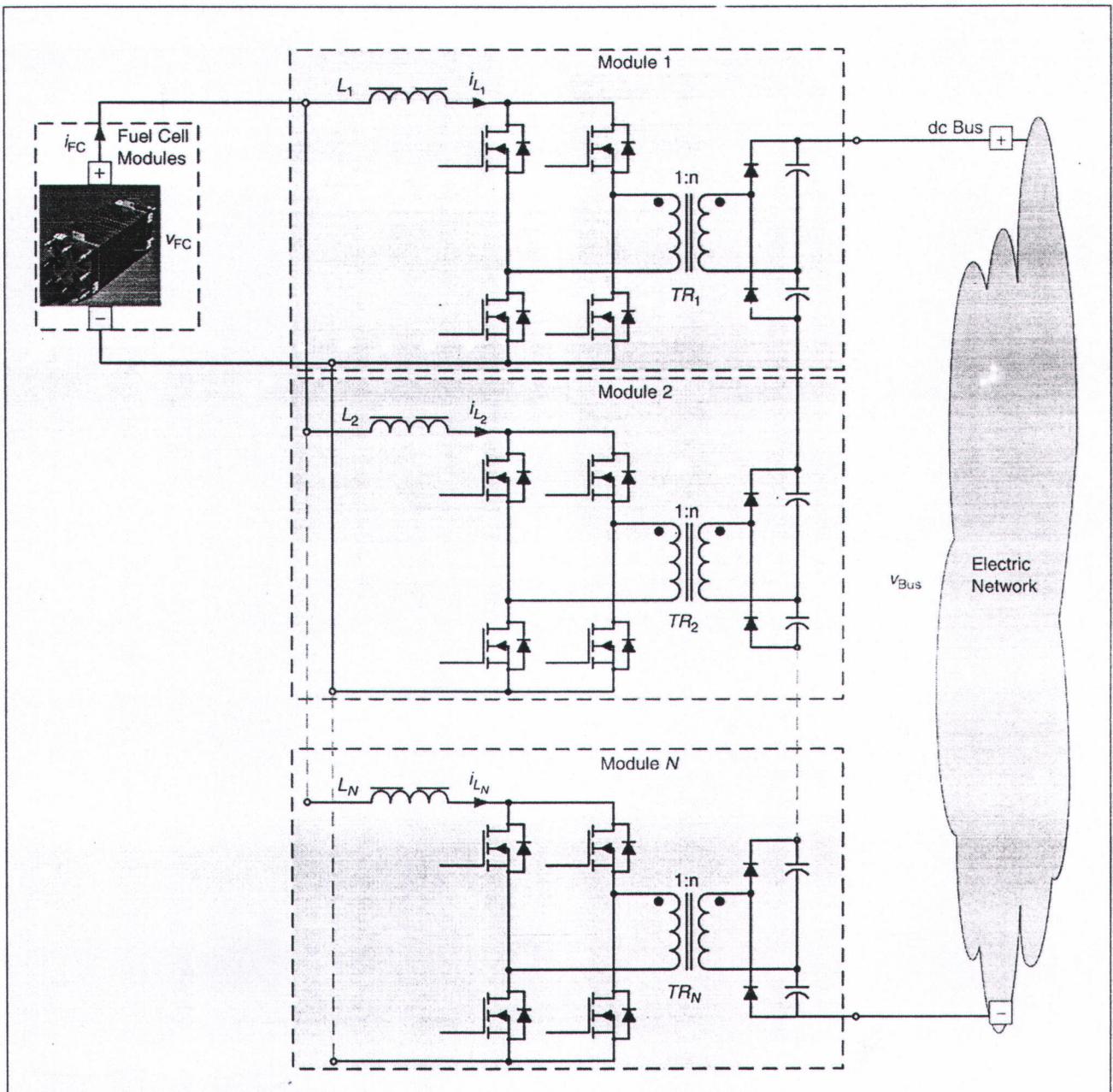


FIGURE 18 – Interleaved current-fed full bridge converters with a parallel input and a series output for FC high power applications.

operate up to 200 kW with the voltage conversion ratio of eight.

For ground isolation and high voltage step-up ratio (but more complicated), interleaved boost/flyback [123], [124], push-pull [125]–[127], and half bridge and full bridge [128]–[132] can be considered as candidate topologies for the FC converter. Advantages and disadvantages of these converters are discussed in [127], [128], and [132]. The most popular ground isolation circuit today for high-power applications is the full-bridge dc/dc converter, because of reasonable device voltage ratings and soft switching possibility [133], [134].

Considering the ripple and direct current control requirement, an isolated current-fed full bridge converter topology shows some promise [134]–[136]. It has small current ripple and high efficiency. To reduce the size of the magnetic components and further improve the converter efficiency, a multiphase interleaved current-fed full-bridge converter is proposed in [113], as shown in Figure 18. By paralleling input of the converter system, input current, and hence the power, can be equally shared between the modules of the converter system. Therefore, current stress on the semiconductor devices on the input side is reduced. On the other hand, the series connection on the output side results in lower voltage ratings for output capacitors and diodes. Furthermore, phase shifted pulse-width modulation (PWM) is used for the interleaved full-bridge converter. So, the input current ripple frequency and the output voltage ripple frequency increase. Hence, for the same input current and output voltage ripple requirement, smaller input inductors and output capacitors can be used.

The advantages of the parallel converter with interleaving technique are as follows:

- 1) Size and volume of passive devices (inductor and capacitor) are reduced.
- 2) Ripple of the input and output waveforms are reduced.
- 3) Ripple frequency of the input and output waveforms are increased
- 4) Power converter is modular. It enhances reliability of the system, and increases converter power

## The power and energy efficiency of an FC is highly dependent on the thermodynamics, electrode kinetics, and reactant mass transfer, as well as materials and components for assembling the FC.

rating by paralleling phases, not by paralleling multiple devices.

- 5) Thermal management is simple. The primary driver in all paralleling schemes for lower power applications is the decentralized heat dissipation of the parallel power converters.
- 6) Current ratings of power electronic components are reduced, because current ratings are proportional to the continuous power rating of the circuit.

### Conclusions

FCs hold great promise as a clean energy conversion technology. A large research effort is underway to develop the FC for applications ranging from small portable electronic devices to automotive transport, as well as residential combined heat and power supplies. These applications have a large emerging market and widespread adoption should lead to a reduced dependence on fossil fuels as well as encourage the development of a hydrogen economy.

FCs produce low dc voltage, so that it is most often connected to electric networks through a step-up dc/dc converter. This article first introduces electrical characteristics, power electronic requirements, and different types of FCs and is then followed by a discussion of the various topologies of step-up dc/dc converters used for FCs' power-conditioning system. The examinations of several different approaches to power-conditioning systems for single and multiple FC combinations have been reviewed.

High-power dc distributed power systems supplied by FC invokes the need to parallel power modules with interleaving technique. By method of the parallel converter modules with interleaving algorithm for an FC generator

for high-power applications, inductor size (ferrite core and Litzwire) are simple to design and fabricate, and the FC ripple current can be virtually reduced to zero. As a result, the FC mean current is nearly equal to the FC rms current. The main drawback of the multiphase approach is added circuit complexity, requiring measurement and balancing of each phase current as the larger number of control components illustrates.

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## There are many different types of FCs, with the principal differences between them being the type of electrolyte and/or the type of fuel that they use.

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### References

- [1] P. Thounthong, B. Davat, and S. Raël, "Drive friendly," *IEEE Power Energy Mag.*, vol. 6, no. 1, pp. 69–76, 2008.
- [2] M. C. Péra, D. Candusso, D. Hissel, and J. M. Kauffmann, "Power generation by fuel cells," *IEEE Ind. Electron. Mag.*, vol. 1, no. 3, pp. 28–37, 2007.
- [3] M. Tekin, D. Hissel, M. C. Péra, and J. M. Kauffmann, "Energy-management strategy for embedded fuel-cell systems using fuzzy logic," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 595–603, Feb. 2007.
- [4] W. Schmittinger and A. Vahidi, "A review of the main parameters influencing long-term performance and durability of PEM fuel cells," *J. Power Sources*, vol. 180, pp. 1–4, May 2008.
- [5] C. Casati, P. Longhi, L. Zanderighi, and F. Bianchi, "Some fundamental aspects in electrochemical hydrogen purification/compression," *J. Power Sources*, vol. 180, pp. 103–113, May 2008.
- [6] C. Kim, K. J. Kim, and M. Y. Ha, "Performance enhancement of a direct borohydride fuel cell in practical running conditions," *J. Power Sources*, vol. 180, pp. 154–161, May 2008.
- [7] S. Varigonda and M. Kamat, "Control of stationary and transportation fuel cell systems: Progress and opportunities," *Comput. Chem. Eng.*, vol. 30, pp. 1735–1748, Sept. 2006.
- [8] Y. Kishinevsky and S. Zelingher, "Coming clean with fuel cells," *IEEE Power Energy Mag.*, vol. 1, pp. 20–25, Nov./Dec. 2003.
- [9] R. von Helmolt and U. Eberle, "Fuel cell vehicles: Status 2007," *J. Power Sources*, vol. 165, pp. 833–843, Mar. 2007.
- [10] V. P. McConnell, "Downsized footprint and material changes for GM's fourth-generation fuel cell technology," *Fuel Cells Bull.*, vol. 2007, pp. 12–15, Jan. 2007.
- [11] K. Bonhoff, "The clean energy partnership Berlin-CEP," *J. Power Sources*, vol. 181, pp. 350–352, July 2008.
- [12] General Motors Corporation. Dow—GM Make World's First Significant Fuel Cell Application a Reality [Online]. Available: [http://www.gm.com/company/gmability/adv\\_tech/500\\_stationary](http://www.gm.com/company/gmability/adv_tech/500_stationary)
- [13] D. Lecocq, "Tomorrow's energy today with Axane," *Fuel Cells Bull.*, vol. 2004, pp. 13–15, Mar. 2004.
- [14] Axane Company. Axane: Products [Online]. Available: <http://www.axane.fr/axane/gb/produits/evopac/concept.html>
- [15] R. J. Wai, C. Y. Lin, R. Y. Duan, and Y. R. Chang, "High-efficiency dc-dc converter with high voltage gain and reduced switch stress," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 354–364, Feb. 2007.
- [16] S. Y. Choe, J. W. Ahn, J. G. Lee, and S. H. Baek, "Dynamic simulator for a PEM fuel cell system

with a PWM dc/dc converter," *IEEE Trans. Energy Conversion*, vol. 23, pp. 669–680, June 2008.

- [17] I. Sadli, P. Thounthong, J. P. Martin, S. Raël, and B. Davat, "Behaviour of a PEMFC supplying a low voltage static converter," *J. Power Sources*, vol. 156, pp. 119–125, May 2006.
- [18] S. C. Page, A. H. Anbuky, S. P. Krumbieck, and J. Brouwer, "Test method and equivalent circuit modeling of a PEM fuel cell in a passive state," *IEEE Trans. Energy Conversion*, vol. 22, pp. 764–773, Sept. 2007.
- [19] S. Pasricha, M. Keppler, S. R. Shaw, and M. H. Nehrir, "Comparison and identification of static electrical terminal fuel cell models," *IEEE Trans. Energy Conversion*, vol. 22, pp. 746–754, Sept. 2007.
- [20] S. R. Choudhury and R. Rengaswamy, "Characterization and fault diagnosis of PAFC cathode by EIS technique and a novel mathematical model approach," *J. Power Sources*, vol. 161, pp. 971–986, Oct. 2006.
- [21] C. Wang and M. H. Nehrir, "A physically based dynamic model for solid oxide fuel cells," *IEEE Trans. Energy Conversion*, vol. 22, pp. 887–897, Dec. 2007.
- [22] M. Suzuki, N. Shikazono, K. Fukagata, and N. Kasagi, "Numerical analysis of coupled transport and reaction phenomena in an anode-supported flat-tube solid oxide fuel cell," *J. Power Sources*, vol. 180, pp. 29–40, May 2008.
- [23] D. H. Ko, M. J. Lee, W. H. Jang, and U. Krewer, "Non-isothermal dynamic modelling and optimization of a direct methanol fuel cell," *J. Power Sources*, vol. 180, pp. 71–83, May 2008.
- [24] M. Paquin and L. G. Fréchette, "Understanding cathode flooding and dry-out for water management in air breathing PEM fuel cells," *J. Power Sources*, vol. 180, pp. 440–451, May 2008.
- [25] U. A. Icardi, S. Specchia, G. J. R. Fontana, G. Saracco, and V. Specchia, "Compact direct methanol fuel cells for portable application," *J. Power Sources*, vol. 176, pp. 460–467, Feb. 2008.
- [26] J. Y. Park, J. H. Lee, J. Kim, S. Han, and I. Song, "Stable operation of air-blowing direct methanol fuel cells with high performance," *J. Power Sources*, vol. 179, pp. 1–8, Apr. 2008.
- [27] S. K. Kamarudin, W. R. W. Daud, S. L. Ho, and U. A. Hasran, "Overview on the challenges and developments of micro-direct methanol fuel cells (DMFC)," *J. Power Sources*, vol. 163, pp. 743–754, Jan. 2007.
- [28] P. C. Buddingh, V. Scaini, and L. F. Casey, "Utilizing waste hydrogen for energy recovery using fuel cells and associated technologies," *IEEE Trans. Ind. Appl.*, vol. 42, pp. 186–194, Jan./Feb. 2006.
- [29] K. Sedghisigarchi and A. Feliachi, "Impact of fuel cells on load-frequency control in power distribution systems," *IEEE Trans. Energy Conversion*, vol. 21, pp. 250–256, Mar. 2006.
- [30] J. Lee, J. Jo, S. Choi, and S. B. Han, "A 10-kW SOFC low-voltage battery hybrid power conditioning system for residential use," *IEEE Trans. Energy Conversion*, vol. 21, pp. 575–585, June 2006.
- [31] Y. H. Li, S. S. Choi, and S. Rajakaruna, "An analysis of the control and operation of a solid oxide fuel-cell power plant in an isolated system," *IEEE Trans. Energy Conversion*, vol. 20, pp. 381–387, June 2005.
- [32] P. Corbo, F. Migliardini, and O. Veneri, "An experimental study of a PEM fuel cell power train for urban bus application," *J. Power Sources*, vol. 181, pp. 363–370, July 2008.
- [33] W. Mitchell, B. J. Bowers, C. Garnier, and F. Boudjemaa, "Dynamic behavior of gasoline fuel cell electric vehicles," *J. Power Sources*, vol. 154, pp. 489–496, Mar. 2006.

- [34] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, pp. 2237–2245, June 2008.
- [35] M. H. Nehrir, C. Wang, and S. R. Shaw, "Fuel cells: promising devices for distributed generation," *IEEE Power Energy Mag.*, vol. 4, pp. 47–53, Jan./Feb. 2006.
- [36] P. Thounthong, S. Raël, and B. Davat, "Test of a PEM fuel cell with low voltage static converter," *J. Power Sources*, vol. 153, pp. 145–150, Jan. 2006.
- [37] P. T. Krein, R. S. Balog, and X. Geng, "High-frequency link inverter for fuel cells based on multiple-carrier PWM," *IEEE Trans. Power Electron.*, vol. 19, pp. 1279–1288, Sept. 2004.
- [38] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell and supercapacitors association for distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 3225–3233, Dec. 2007.
- [39] J. M. Corrêa, F. A. Farret, L. N. Canha, and M. G. Simões, "An electrochemical-based fuel-cell model suitable for electrical engineering automation approach," *IEEE Trans. Ind. Electron.*, vol. 51, pp. 1103–1112, Oct. 2004.
- [40] J. M. Corrêa, F. A. Farret, V. A. Popov, and M. G. Simões, "Sensitivity analysis of the modeling s used in simulation of proton exchange membrane fuel cells," *IEEE Trans. Energy Conversion*, vol. 20, pp. 211–218, Jan./Mar. 2005.
- [41] T. Zhu, S. R. Shaw, and S. B. Leeb, "Transient recognition control for hybrid fuel cell systems," *IEEE Trans. Energy Conversion*, vol. 21, pp. 195–201, Mar. 2006.
- [42] F. Jurado, "Novel fuzzy flux control for fuel-cell inverters," *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1707–1716, Dec. 2005.
- [43] C. Wang and M. H. Nehrir, "Load transient mitigation for stand-alone fuel cell power generation systems," *IEEE Trans. Energy Conversion*, vol. 22, pp. 864–872, Dec. 2007.
- [44] P. Thounthong, S. Raël, and B. Davat, "DC bus voltage regulation supplied by fuel cell/supercapacitor hybrid source," *ECTI Trans. Electrical Eng., Electron., and Commun.*, vol. 4, pp. 90–95, Aug. 2006.
- [45] R. Gaynor, F. Mueller, F. Jabbari, and J. Brouwer, "On control concepts to prevent fuel starvation in solid oxide fuel cells," *J. Power Sources*, vol. 180, pp. 330–342, May 2006.
- [46] M. Meiler, O. Schmid, M. Schudy, and E. P. Hofer, "Dynamic fuel cell stack model for real-time simulation based on system identification," *J. Power Sources*, vol. 176, pp. 523–528, Feb. 2008.
- [47] J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, "Controlling fuel cell breathing," *IEEE Control Syst. Mag.*, vol. 24, no. 2, pp. 30–46, Apr. 2004.
- [48] P. Thounthong, S. Raël, and B. Davat, "Fuel cell and supercapacitors for automotive hybrid electrical system," *ECTI Trans. Elect. Eng., Electron. Commun.*, vol. 3, pp. 20–30, Feb. 2005.
- [49] A. Taniguchi, T. Akita, K. Yasuda, and Y. Miyazaki, "Analysis of electrocatalyst degradation in PEMFC caused by cell reversal during fuel starvation," *J. Power Sources*, vol. 130, pp. 42–49, May 2004.
- [50] P. Thounthong, "Control of fuel cell/battery hybrid source for electric vehicle applications," *ECTI Trans. Elect. Eng., Electron. Commun.*, vol. 5, pp. 192–198, Aug. 2007.
- [51] P. Rodatz, G. Paganelli, A. Sciarretta, and L. Guzzella, "Optimal power management of an experimental fuel cell/supercapacitor-powered hybrid vehicle," *Control Eng. Practice*, vol. 13, no. 1, pp. 41–53, Jan. 2005.
- [52] P. Corbo, F. E. Corcione, F. Migliardini, and O. Veneri, "Experimental study of a fuel cell power train for road transport application," *J. Power Sources*, vol. 145, pp. 610–619, Aug. 2005.
- [53] P. Thounthong, S. Raël, and B. Davat, "Supercapacitors as an energy storage for fuel cell automotive hybrid electrical system," *J. Elect. Eng. Transport.*, vol. 1, pp. 21–25, no. 1, 2005.
- [54] R. S. Gemmen, "Analysis for the effect of inverter ripple current on fuel cell operating condition," *Trans. ASME, J. Fluids Eng.*, vol. 125, pp. 576–585, May 2003.
- [55] W. Choi, G. Joung, P. N. Enjeti, and J. W. Howze, "An experimental evaluation of the effects of ripple current generated by the power conditioning stage on a proton exchange membrane fuel cell stack," *Trans. ASME, J. Mater. Eng. Perform.*, vol. 13, pp. 257–264, Aug. 2004.
- [56] A. Sakhare, A. Davari, and A. Feliachi, "Fuzzy logic control of fuel cell for stand-alone and grid connection," *J. Power Sources*, vol. 135, pp. 165–176, Sept. 2004.
- [57] K. Sedghisigarchi and A. Feliachi, "Dynamic and transient analysis of power distribution systems with fuel cells-Part II: control and stability enhancement," *IEEE Trans. Energy Conversion*, vol. 19, pp. 429–434, June 2004.
- [58] D. B. Nelson, M. H. Nehrir, and V. Gerez, "Economic evaluation of grid-connected fuel-cell systems," *IEEE Trans. Energy Conversion*, vol. 20, pp. 452–458, June 2005.
- [59] P. Thounthong and B. Davat, "A PEM fuel cell power source for electric vehicle applications with supercapacitor or battery as auxiliary," in *Progress in Fuel Cell Research*. P. V. Aleme, Ed. Commack, NY: Nova, 2007, ch. 8.
- [60] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, pp. 2258–2267, June 2008.
- [61] M. J. Kim and H. Peng, "Power management and design optimization of fuel cell/battery hybrid vehicles," *J. Power Sources*, vol. 165, pp. 819–832, Mar. 2007.
- [62] R. Lallemand, A. De Bernardinis, G. Coquery, J. P. Ousten, S. Raël, and B. Davat, "Active load for fuel cell system dedicated to transportation applications," in *Proc. EPE'03*, Toulouse, France, Oct. 2003.
- [63] T. Furuya, K. Kondo, and T. Yamamoto, "Experimental study on a PEMFC fed railway vehicle motor drive system," in *Proc. 41st IEEE-IAS*, 8–12 Oct. 2006, pp. 1249–1252.
- [64] T. Montani, "Electric energy storage evaluation for urban rail vehicles," in *Proc. EPE'03*, Toulouse, France, Oct. 2003.
- [65] L. U. Gökdere, K. Benlyazid, R. A. Dougal, E. Santi, and C. W. Brice, "A virtual prototype for a hybrid electric vehicle," *Mechatronics*, vol. 12, pp. 575–593, May 2002.
- [66] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Conversion*, vol. 23, pp. 148–155, Mar. 2008.
- [67] J. Gonzales and G. Tamizhmani, "High efficiency fuel cell based uninterruptible power supply for digital equipment," *J. Power Sources*, vol. 153, pp. 151–156, Jan. 2006.
- [68] P. Corbo, F. E. Corcione, F. Migliardini, and O. Veneri, "Experimental assessment of energy-management strategies in fuel-cell propulsion systems," *J. Power Sources*, vol. 157, pp. 799–808, July 2006.
- [69] A. Folkesson, C. Andersson, P. Alvfors, M. Alakula, and L. Overgaard, "Real life testing of a hybrid PEM fuel cell bus," *J. Power Sources*, vol. 118, no. 1–2, pp. 349–357, May 2003.
- [70] K. S. Jeong, W. Y. Lee, and C. S. Kim, "Energy management strategies of a fuel cell/battery hybrid system using fuzzy logics," *J. Power Sources*, vol. 145, pp. 319–326, Aug. 2005.
- [71] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle," *J. Power Sources*, vol. 158, no. 1, pp. 806–814, July 2006.
- [72] R. Kötz, J. C. Sauter, P. Ruch, P. Dietrich, F. N. Büchi, P. A. Magne, and P. Varenne, "Voltage balancing: Long-term experience with the 250 V supercapacitor module of the hybrid fuel cell vehicle HY-LIGHT," *J. Power Sources*, vol. 174, pp. 264–271, Nov. 2007.
- [73] M. Uzunoglu and M. S. Alam, "Dynamic modeling, design, and simulation of a combined PEM fuel cell and ultracapacitor system for standalone residential applications," *IEEE Trans. Energy Conversion*, vol. 21, pp. 767–775, Sept. 2006.
- [74] T. H. Bradley, B. A. Moffitt, D. N. Mavris, and D. E. Parekh, "Development and experimental characterization of a fuel cell powered aircraft," *J. Power Sources*, vol. 171, pp. 793–801, Sept. 2007.
- [75] N. Lapena-Rey, J. Mosquera, E. Bataller, F. Orti, C. Dudfield, and A. Orsillo, "Environmentally friendly power sources for aerospace applications," *J. Power Sources*, vol. 181, pp. 353–362, July 2008.
- [76] T. L. Cable and S. W. Sofie, "A symmetrical, planar SOFC design for NASA's high specific power density requirements," *J. Power Sources*, vol. 174, pp. 221–227, Nov. 2007.
- [77] A. K. Sehra and W. Whitlow, Jr., "Propulsion and power for 21st century aviation," *Progress Aerosp. Sciences*, vol. 40, pp. 199–235, May–July 2004.
- [78] J. Dollmayer, N. Bunschuh, and U. B. Carl, "Fuel mass penalty due to generators and fuel cells as energy source of the all-electric aircraft," *Aerosp. Sci. Technol.*, vol. 10, pp. 686–694, Dec. 2006.
- [79] M. Granovskii, I. Dincer, and M. A. Rosen, "Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles," *J. Power Sources*, vol. 159, pp. 1186–1193, Sept. 2006.
- [80] W. Kempton and T. Kubo, "Electric-drive vehicles for peak power in Japan," *Energy Policy*, vol. 28, pp. 9–18, Jan. 2000.
- [81] T. Aicher, B. Lenz, F. Gschnell, U. Groos, F. Federici, L. Caprile, and L. Parodi, "Fuel processors for fuel cell APU applications," *J. Power Sources*, vol. 154, pp. 503–508, Mar. 2006.
- [82] O. Bitsche and G. Gutmann, "Systems for hybrid cars," *J. Power Sources*, vol. 127, pp. 8–15, Mar. 2004.
- [83] R. M. Moore, K. H. Hauer, S. Ramaswamy, and J. M. Cunningham, "Energy utilization and efficiency analysis for hydrogen fuel cell vehicles," *J. Power Sources*, vol. 159, pp. 1214–1230, Sept. 2006.
- [84] P. Fontela, A. Soria, J. Mielgo, J. F. Sierra, J. de Blas, L. Gauchia, and J. M. Martinez, "Airport electric vehicle powered by fuel cell," *J. Power Sources*, vol. 169, pp. 184–193, June 2007.
- [85] B. J. Bowers, J. L. Zhao, M. Ruffo, R. Khan, D. Dattatraya, N. Dushman, J. C. Beziat, and F. Boudjema, "Onboard fuel processor for PEM fuel cell vehicles," *Int. J. Hydrogen Energy*, vol. 32, pp. 1437–1442, July–Aug. 2007.
- [86] J. Ally and T. Pryor, "Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems," *J. Power Sources*, vol. 170, pp. 401–411, July 2007.

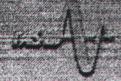
- [87] M. Kim, Y. J. Sohn, W. Y. Lee, and C. S. Kim, "Fuzzy control based engine sizing optimization for a fuel cell/battery hybrid mini-bus," *J. Power Sources*, vol. 178, pp. 706–710, Apr. 2008.
- [88] M. Saxe, A. Folkesson, and P. Alvfors, "Energy system analysis of the fuel cell buses operated in the project: Clean urban transport for Europe," *Energy*, vol. 33, pp. 689–711, May 2008.
- [89] A. R. Miller, K. S. Hess, D. L. Barnes, and T. L. Erickson, "System design of a large fuel cell hybrid locomotive," *J. Power Sources*, vol. 173, pp. 935–942, Nov. 2007.
- [90] A. R. Miller, J. Peters, B. E. Smith, and O. A. Velev, "Analysis of fuel cell hybrid locomotives," *J. Power Sources*, vol. 157, pp. 855–861, July 2006.
- [91] T. Yoneyama, T. Yamamoto, K. Kondo, T. Furuya, and K. Ogawa, "Fuel cell powered railway vehicle and experimental test results," in *Proc. EPE'07*, 2–5 Sept. 2007, pp. 1–10.
- [92] T. Ogawa, H. Yoshihara, S. Wakao, K. Kondo, and M. Kondo, "Energy consumption analysis of FC-EDLC hybrid railway vehicle by dynamic programming," in *Proc. EPE'07*, 2–5 Sept. 2007, pp. 1–10.
- [93] C. Wang, M. H. Nehrir, and H. Gao, "Control of PEM fuel cell distributed generation systems," *IEEE Trans. Energy Conversion*, vol. 21, pp. 586–595, June 2006.
- [94] A. de Bernardinis, M. C. Péra, J. Garnier, D. Hissel, G. Coquery, and J. M. Kauffmann, "Fuel cells multi-stack power architectures and experimental validation of 1 kW parallel twin stack PEFC generator based on high frequency magnetic coupling dedicated to on board power unit," *Energy Conversion Manage.*, vol. 49, pp. 2367–2383, Aug. 2008.
- [95] B. Ozpineci, L. M. Tolbert, and Z. Du, "Multiple input converters for fuel cells," in *Proc. IEEE-IAS 2004*, 3–7 Oct. 2004, vol. 2, pp. 791–797.
- [96] D. B. Viet, Y. Lembeye, J. P. Ferriux, J. Barbaroux, and Y. Avenas, "New high power—High ratio non isolated DC-DC boost converter for fuel cell applications," in *Proc. IEEE-PESC'06*, Jeju, Korea, pp. 1148–1154.
- [97] L. Palma and P. Enjeti, "A modular fuel cell, modular DC-DC converter concept for high performance and enhanced reliability," in *Proc. IEEE-PESC 2007*, 17–21 June 2007, pp. 2633–2638.
- [98] B. Vulturescu, A. De Bernardinis, R. Lallemand, and G. Coquery, "Traction power converter for PEM fuel cell multi-stack generator used in urban transportation," in *Proc. EPE'07*, 2–5 Sept. 2007, pp. 1–10.
- [99] K. Agbossou, M. Kolhe, J. Hamelin, and T. K. Bose, "Performance of a stand-alone renewable energy system based on energy storage as hydrogen," *IEEE Trans. Energy Conversion*, vol. 19, pp. 633–640, Sept. 2004.
- [100] R. J. Wai, R. Y. Duan, J. D. Lee, and L. W. Liu, "High-efficiency fuel-cell power inverter with soft-switching resonant technique," *IEEE Trans. Energy Conversion*, vol. 20, pp. 485–492, June 2005.
- [101] W. Choi, J. W. Howze, and P. Enjeti, "Fuel-cell powered uninterruptible power supply systems: Design considerations," *J. Power Sources*, vol. 157, pp. 311–317, June 2006.
- [102] B. Fahimi, A. Emadi, and R. B. Sepe, Jr., "Switched reluctance machine-based starter/alternator for more electric cars," *IEEE Trans. Energy Conversion*, vol. 19, pp. 116–124, Mar. 2004.
- [103] T. A. Keim, "Systems for 42 V mass-market automobiles," *J. Power Sources*, vol. 127, pp. 16–26, Mar. 2004.
- [104] L. Nicod, "Energy strategy and optimization on hybrid light rail vehicle," in *Proc. EPE'03*, 2003.
- [105] J. M. Andujar, F. Segura, and M. J. Vasallo, "A suitable model plant for control of the set fuel cell-DC/DC converter," *Renewable Energy*, vol. 33, pp. 813–826, Apr. 2008.
- [106] M. Mohr and F. W. Fuchs, "Comparison of three phase current source inverters and voltage source inverters linked with dc to dc boost converters for fuel cell generation systems," in *Proc. EPE'05*, 11–14 Sept. 2005, pp. 1–10.
- [107] J. J. Brey, C. R. Bordallo, J. M. Carrasco, E. Galvan, A. Jimenez, and E. Moreno, "Power conditioning of fuel cell systems in portable applications," *Int. J. Hydrogen Energy*, vol. 32, pp. 1559–1566, July–Aug. 2007.
- [108] J. J. Lee and B. H. Kwon, "DC-DC converter using a multiple-coupled inductor for low output voltages," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 467–478, Feb. 2007.
- [109] Y. K. Lo, T. S. Kao, and J. Y. Lin, "Analysis and design of an interleaved active-clamping forward converter," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 2323–2332, Aug. 2007.
- [110] H. Mao, L. Yao, C. Wang, and I. Batarseh, "Analysis of inductor current sharing in nonisolated and isolated multiphase dc-dc converters," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 3379–3388, Dec. 2007.
- [111] M. Baumann and J. W. Kolar, "Parallel connection of two three-phase three-switch buck-type unity-power-factor rectifier systems with DC-link current balancing," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 3042–3053, Dec. 2007.
- [112] A. Lidozzi, V. Serrao, L. Solero, and F. Crésimbini, "Power electronic converters distribution in HOST hybrid propulsion system," in *Proc. EPE'07*, 2007.
- [113] X. Kong and A. M. Khambadkone, "Analysis and implementation of a high efficiency, interleaved current-fed full bridge converter for fuel cell system," *IEEE Trans. Power Electron.*, vol. 22, pp. 543–550, Mar. 2007.
- [114] P. Thounthong, P. Sethakul, S. Raël, and B. Davat, "Design and Implementation of 2-Phase Interleaved Boost Converter for Fuel Cell Power Source," in *Proc. IET-PEMD 2008*, 2–4 Apr. 2008, York, U.K., pp. 91–95.
- [115] P. Thounthong, P. Sethakul, S. Raël, and B. Davat, "Modeling and control of a fuel cell current control loop of a 4-phase interleaved step-up converter for dc distributed system," in *Proc. 39th IEEE-PESC*, 15–19 June 2008, Island of Rhodes, Greece, pp. 230–236.
- [116] J. C. Hwang, L. H. Chen, and S. N. Yeh, "Comprehensive analysis and design of multi-leg fuel cell boost converter," *Appl. Energy*, vol. 84, pp. 1274–1288, Dec. 2007.
- [117] H. Xu, E. Qiao, X. Guo, X. Wen, and L. Kong, "Analysis and design of high power interleaved boost converters for fuel cell distributed generation system," in *Proc. PESC'05*, 11–14 Sept. 2005, pp. 140–145.
- [118] S. Ponnaluri, G. O. Linhofer, J. K. Steinke, and P. K. Steimer, "Comparison of single and two stage topologies for interface of BESS or fuel cell system using the ABB standard power electronics building blocks," in *Proc. EPE'05*, 2005, pp. 1–9.
- [119] H. Hinz, "A simulation model for the analysis and design of the electric power conversion system in fuel cell vehicles," in *Proc. EPE'03*, pp. 1–9.
- [120] B. Huang, I. Sadli, J. P. Martin, and B. Davat, "Design of a high power, high step-up non-isolated dc-dc converter for fuel cell applications," in *Proc. IEEE-VPPC'06*, 6–8 Sept. 2006, pp. 1–6.
- [121] B. Huang, J. P. Martin, S. Pierfederici, and B. Davat, "High voltage ratio non-isolated dc-dc Converter for fuel cell power source applications," in *Proc. 39th IEEE-PESC*, 15–19 June 2008, Island of Rhodes, Greece, pp. 1277–1283.
- [122] L. Palma, M. H. Todorovic, and P. Enjeti, "A high gain transformer-less dc-dc converter for fuel-cell applications," in *Proc. IEEE-PESC'05*, pp. 2514–2520.
- [123] R. Attanasio, M. Cacciato, A. Consoli, G. Scarcella, A. Testa, and F. Gennaro, "A novel converter system for fuel cell distributed energy generation," in *Proc. IEEE-PESC'05*, pp. 1621–1627.
- [124] S. de Caro, A. Testa, D. Triolo, M. Cacciato, and A. Consoli, "Low input current ripple converters for fuel cell power units," in *Proc. EPE'05*, 2005.
- [125] G. Wang, P. Pant, H. Mohammad, P. Famouri, and O. Demirci, "High efficiency low cost inverter system for fuel cell application," in *Proc. 2003 Fuel Cell Seminar: Special Session on Fuel Cell Power Conditioning*, 3 Nov. 2003, Miami, Florida, pp. 16–20.
- [126] M. H. Todorovic, L. Palma, W. Choi, C. Dowling, D. Humphrey, D. Tarbell, P. Enjeti, and J. Howze, "Development of a low cost fuel cell inverter system with DSP control for residential use," in *Proc. 2003 Fuel Cell Seminar: Special Session on Fuel Cell Power Conditioning*, 3 Nov. 2003, Miami, Florida, pp. 27–32.
- [127] H. Wetzel, N. Fröhleke, J. Böcker, P. Ide, and J. Kunze, "Fuel cell inverter system with integrated auxiliary supply," in *Proc. EPE'05*.
- [128] T. P. Bohn and R. D. Lorenz, "A low-cost inverter for domestic fuel cell applications," in *Proc. 2003 Fuel Cell Seminar: Special Session on Fuel Cell Power Conditioning*, 3 Nov. 2003, Miami, Florida, pp. 41–48.
- [129] D. Georgakis, S. Papanthanasios, and S. Manias, "Modeling and control of a small scale grid-connected PEM fuel cell system," in *Proc. IEEE-PESC'05*, 2005, pp. 1614–1620.
- [130] H. Tao, J. L. Duarte, and M. A. M. Hendrix, "High-resolution phase shift and digital implementation of a fuel cell powered UPS system," in *Proc. EPE'07*, 2007.
- [131] A. Avergerg and A. Mertens, "Design considerations of a voltage-fed full bridge dc-dc converter with high voltage gain for fuel cell applications," in *Proc. EPE'07*, 2007, pp. 1–11.
- [132] D. K. Choi, B. K. Lee, S. W. Choi, C. Y. Won, and D. W. Yoo, "A novel power conversion circuit for cost-effective battery-fuel cell hybrid systems," *J. Power Sources*, vol. 152, pp. 245–255, Dec. 2005.
- [133] R. Bojoi, G. Griva, G. Kovačević, and A. Tenconi, "ZVS-ZCS full-bridge dc-dc converter for voltage step-up in fuel cell distributed generation systems," in *Proc. EPE'07*, 2007, pp. 1–8.
- [134] X. Zhu, D. Xu, G. Shen, D. Xi, K. Mino, and H. Umida, "Current-fed dc/dc converter with reverse block IGBT for fuel cell distributing power system," in *Proc. IEEE-IAS'05*, 2005, pp. 2043–2048.
- [135] H. Mehlich, S. Jaehnert, J. Mehlich, B. Veit, and S. König, "A current-controlled fuel cell system with short-time storage for grid feeding application," in *Proc. EPE'07*, 2007.
- [136] M. Mohr and F. W. Fuchs, "Clamping for current-fed dc/dc converters with recovery of clamping energy in fuel cell inverter systems," in *Proc. EPE'07*, 2007. 

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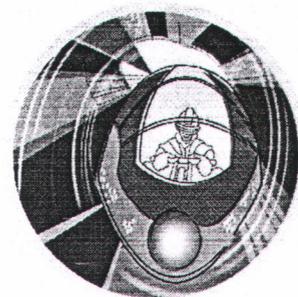
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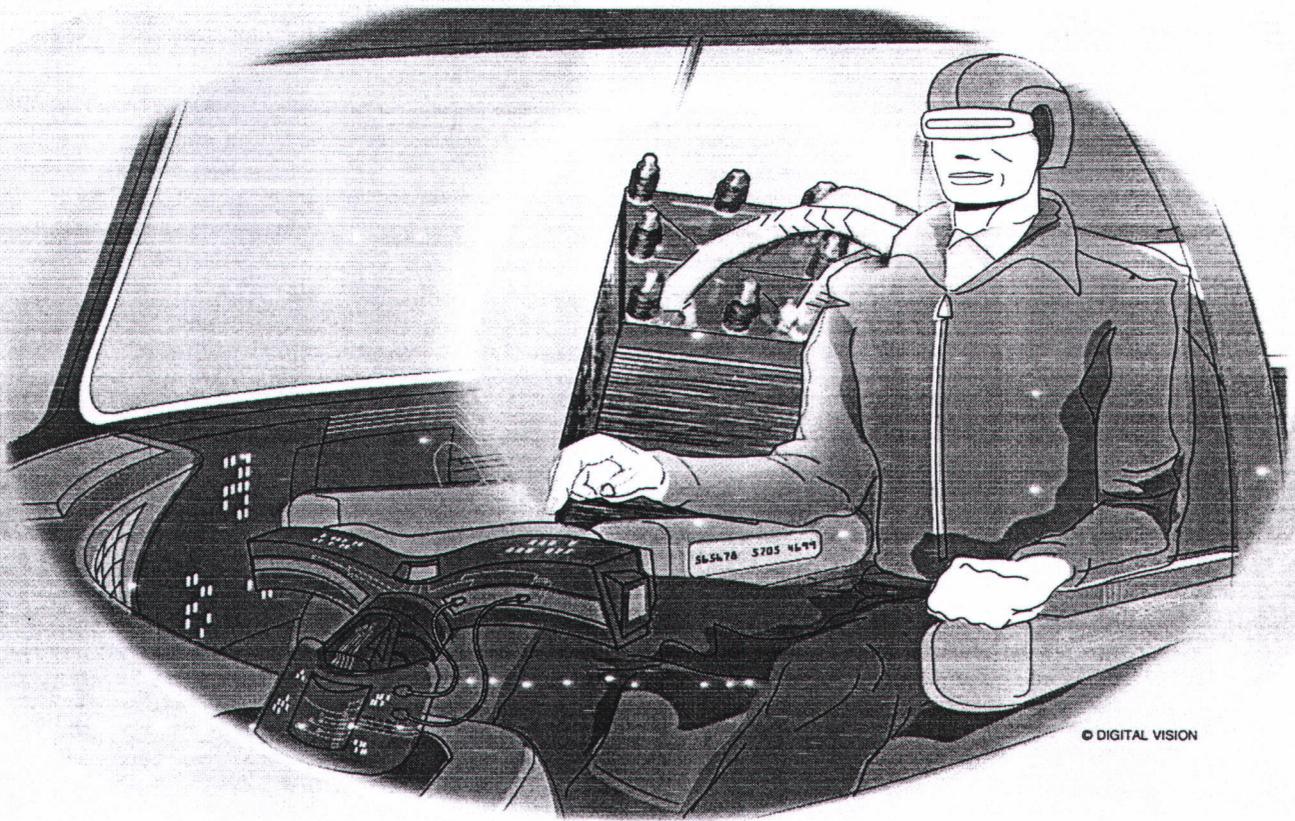
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# FUEL STARVATION



## Analysis of a PEM fuel-cell system

**I**N THIS DAY AND AGE, FUEL CELLS (FCs) are under research as possible alternative power sources for the future. Modern FC development arose from an infusion of research money by several research agencies, including the U.S. Department of Energy (DOE) and the French National Center for Scientific Research (CNRS). Earlier, the first used FC has been employed to produce electrical power in space vehicles by the National Aeronautics and Space Administration

(NASA) as a part of the Gemini program [1]. It is still in use today in the space transportation system (STS) shuttle orbiters. Many previous works have already highlighted the possibility of using the FC in distributed power generation systems: in portable applications [2], [3], transportation applications [4], [5], and stationary power applications [6], [7].

There are many types of FCs characterized by their electrolytes. One of the most promising to be used in electric vehicle applications is the polymer electrolyte membrane FC (PEMFC) because of its relatively small size, light weight, and ease to build [8], [9].

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& PANARIT SETHAKUL

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In 1966, General Motors (GM; USA) became the first automaker to demonstrate a drivable FC vehicle named the Electrovan. Today, many automobile companies (such as GM, Renault, Opel, Suzuki, Toyota, Daihatsu, DaimlerChrysler, Ford, Mazda) have demonstrated the possibilities of using the PEMFC as a main source in electric vehicles called FC vehicles (FCVs). The concept of an FCV is depicted in Figure 1.

For example, after a long history of FC research and development from 1964, GM unveiled an FCV powered by PEMFC (75 kW, 125–200 V, 200 cells) to drive a wheel motor (a permanent magnet synchronous: 60 kW, 305 Nm) with a driving range of 400 km in 2000. In the United States, in 2002, the Honda FCX was the first FC car to be certified for use by the general public, and so theoretically become publicly available. This four-seater city car has a top speed of 150 km/h and a range of 270 km. The hydrogen fuel is stored in a high-pressure tank [10].

In industry, United Technologies Corporation (UTC) FC (USA) is involved in the development of the FC systems for space and defense applications. UTC FC activity began in 1958 and led to the development of the first practical FC application used to generate electrical power and potable water for the Apollo space missions. In 1998, UTC FC delivered a 100-kW FC power plant, with 40% efficiency, to Nova Bus for installation in a 40-ft, hybrid-drive electric bus under a DOE/Georgetown University contract [11].

GM is involved in the development of PEMFCs for stationary power and the more obvious automotive markets [12]. In February 2004, they began the first phase of installation operations in Texas at Dow's chemical manufacturing, the largest facility in the world. These FC systems are used to generate 35 MW of electricity.

Axane (France) was created in 2001 and is working on PEM FC technology [13]. It is positioning itself to the objective three markets that are likely to provide large commercial outlets in the short term:

- 1) portable multiapplication generators (500 W–10 kW),
- 2) stationary applications (more than 10 kW),
- 3) mobile applications for small hybrid vehicles (5 kW–20 kW).

Nonetheless, it is widely accepted that one of the key weak points of the FC systems is their dynamic limitation, according to recent research studies by Thounthong et al. [14], who worked with a 0.5-kW PEMFC, and by Gaynor et al. [15], who worked with a 350-kW solid oxide FC. The FC system's time constant is dominated by the compressor and the membrane hydration level, and it may be several hundredths of a millisecond. As a result, fast load demand will cause a high-voltage drop in a short time, which is recognized as a fuel starvation phenomenon [16], [17]. Fuel or oxidant starvation refers to the operation of FCs at substoichiometric reaction conditions. When starved from fuel or oxygen, the FC performance

degrades and the cell-voltage drops. This condition of operation is evidently hazardous for the FC stack [18].

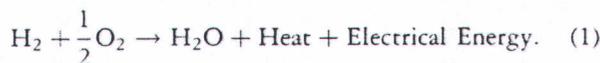
The main aim of this study is to reveal the FC characteristics: static and dynamic, particularly the fuel starvation phenomenon. So, the analysis of fuel starvation problem presented here is the original study in the domain of FC scientific research. The low voltage of an FC source is adapted to a higher level by a classical boost converter. This converter operates as an electrical load. In this case, the FC naturally functions in the environment of power electronic converter at a high-switching frequency. In addition, the FC current is controlled by an analog proportional-integral-derivative (PID) controller. Experimental results with a PEMFC (500 W, 40 A) will clearly illustrate the FC characteristics.

## PEMFC

### FC Principle

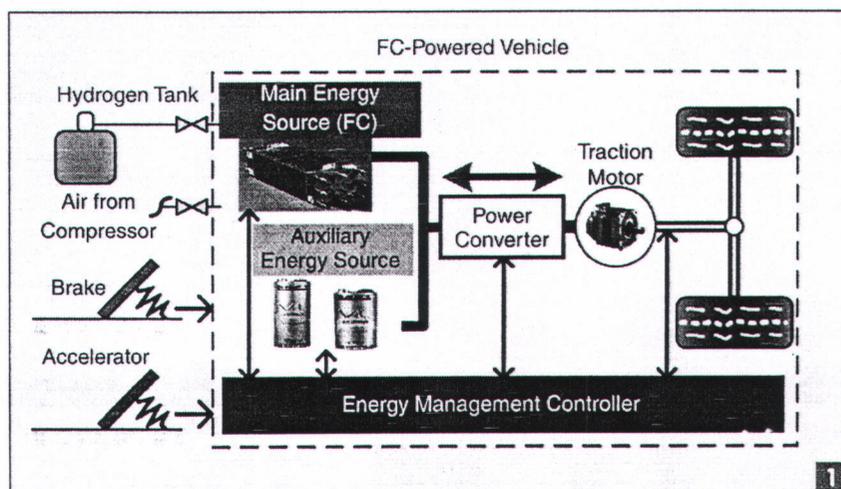
FCs are electrochemical devices that directly convert the chemical energy of a fuel into electricity. FCs operate continuously as long as they are provided with reactant gases. In the case of hydrogen/oxygen FCs, which are the focus of most research activities today, the only by-product is water and heat [19], [20].

The FC model here is for a type of PEM, which uses the following electrochemical reaction:



As developed earlier [21], [22], the Nernst equation for the hydrogen/oxygen FC, using literature values for the standard-state entropy change, can be written as

$$E = \left\{ 1.229 - 0.85 \times 10^{-3} \cdot (T - 298.15) + 4.3085 \times 10^{-5} T \cdot \left[ \ln(p_{\text{H}_2}) + \frac{1}{2} \ln(p_{\text{O}_2}) \right] \right\} \cdot n_{\text{Cell}}, \quad (2)$$



Concept of an FCV.

where  $E$  is the reversible no-loss voltage of the FC (the thermodynamic potential),  $T$  is the cell temperature (K),  $p_{H_2}$  and  $p_{O_2}$  are the partial pressure of hydrogen and oxygen (bar), respectively, and  $n_{\text{Cell}}$  is the number of cells in series.

The FC voltage  $V_{\text{FC}}$  is modeled as [21], [22]

$$V_{\text{FC}} = E - \underbrace{A \cdot \log\left(\frac{I_{\text{FC}} + i_n}{i_0}\right)}_{\text{Activation loss}} - \underbrace{R_m \cdot (I_{\text{FC}} + i_n)}_{\text{Ohmic loss}} + \underbrace{B \cdot \log\left(1 - \frac{I_{\text{FC}} + i_n}{i_L}\right)}_{\text{Concentration loss}}, \quad (3)$$

where  $I_{\text{FC}}$  is the delivered FC current,  $i_0$  is the exchange current,  $A$  is the slope of the Tafel line,  $i_L$  is the limiting current,  $B$  is the constant in the mass transfer term,  $i_n$  is the internal current, and  $R_m$  is the membrane and contact resistances. These parameters can be determined from experiments.

### FC System

An FC is always an assembly of elementary cells that constitute a stack. In particular, Figure 2(a) presents the PEM

FC stack developed by the Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), Ulm, Germany. This stack is also used in the experiment. Its serpentine flow-field plate is also illustrated in Figure 2(b). In a single FC, these two plates are the last of the components making up the cell.

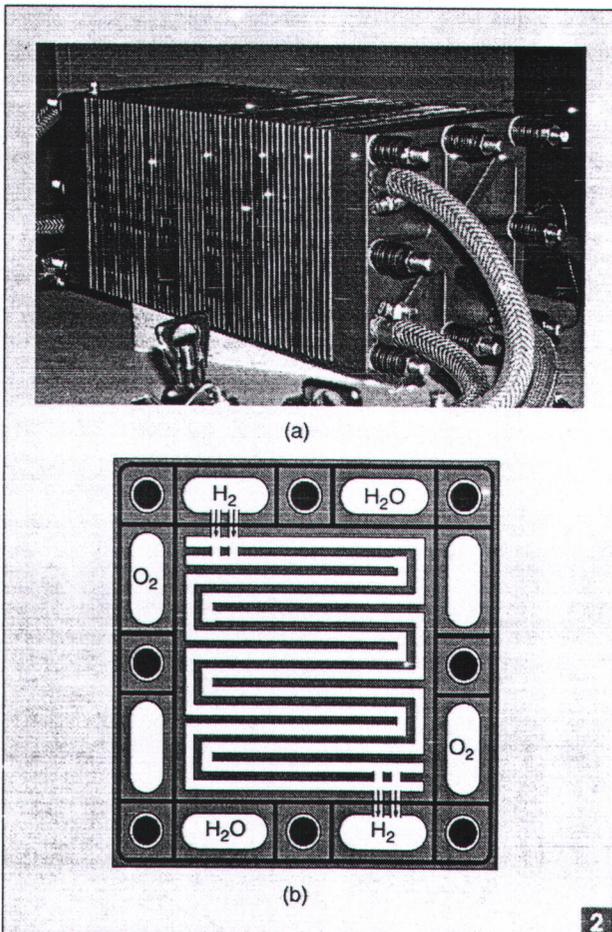
The plates are made of a light weight, strong, gas-impermeable, electron-conducting material; graphite or metals are commonly used. The first task performed by each plate is to provide a gas flow field. The channels are used to carry the reactant gas from the point at which it enters the FC to the point at which the gas exits. Flow-field design also affects water supply to the membrane and water removal from the cathode. The second task served by each plate is that of current collector. With the addition of the flow fields and current collectors, the PEMFC is completed.

Figure 2(a) shows some of the tubes that deliver gases. There are usually  $2 \times 4$  connections: two wires for the current,  $2 \times 2$  tubes for the gases, and  $1 \times 2$  tubes for the cooling system. As the gases are supplied in excess to ensure a good operation of the cell, the nonconsumed gases have to leave the FC carrying with them the produced water (Figure 3). Generally, a water circuit is used to impose the operating temperature of the FC (approximately 60–70 °C). At start up, the FC stack is warmed and later cooled at the rated current. Nearly, the same amount of energy generated is heat and electricity.

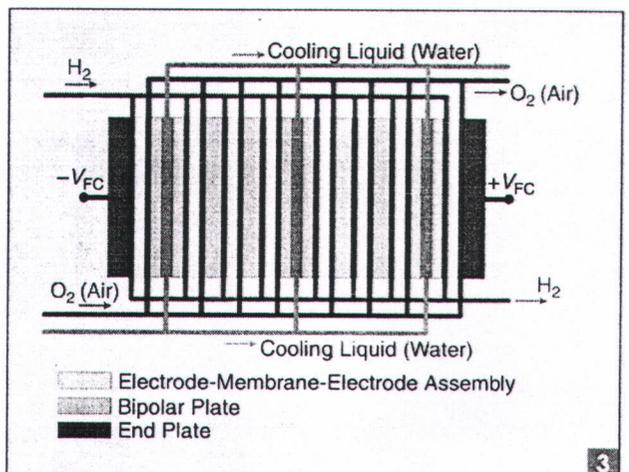
An FC stack requires fuel, oxidant, and coolant to operate. The pressure and flow rate of each of these streams must be regulated. The gases must be humidified, and the coolant temperature must be controlled. To achieve this, the FC stack must be surrounded by a fuel system, fuel delivery system, air system, stack cooling system, and humidification system.

Once operating, the output power must be conditioned. Suitable alarms must shut down the process if unsafe operating conditions occur, and a cell-voltage monitoring system must monitor FC stack performance. These functions are performed by the electrical control systems.

Figure 4 shows the simplified diagram of the PEMFC system of the stack presented in Figure 2. When an FC system is operated, its fuel flows are controlled by an FC controller that receives an FC current demand (reference),  $i_{\text{FCREF}}$ , from the user (manual operation) or from the



PEMFC (23 cells, 500 W, 40 A, around 13 V): (a) stack and (b) a serpentine flow field plate of 100 cm<sup>2</sup>. Pressed against the outer surface of each backing layer is a piece of hardware, called a plate, which often serves the dual role of flow field and current collector.



External and internal connections of a PEMFC stack.

energy-management controller (in case of automatic operation) [23]. The fuel flows must be adjusted to match the reactant delivery rate to the usage rate by the FC controller. For the FC system considered here, the FC current demand signal  $i_{FCREF}$  is in a linear scale of 50 A/10 V [23]. As an example, Figure 5 illustrated a PEMFC system (1.2 kW, 46 A), the first commercial PEMFC, fabricated and commercialized by the Ballard Power Systems Inc.

### FC Power Conditioning

To adapt the low dc voltage of the FC to a higher dc bus voltage  $v_{Bus}$ , a classical boost converter is always selected as an FC converter [24], [25], as depicted in Figure 6. In this system, the FC generator is followed by the converter comprising a controlled switch  $S_1$  (such as a power MOSFET), a high-frequency inductor  $L_1$ , an output filtering capacitor  $C_{Bus}$ , and a diode  $D_1$ . The FC converter is driven, through MOSFET  $S_1$  gate signal, by means of a pulse-width modulation (PWM) for average current control in continuous conduction mode, to obtain a constant switching frequency [14].

Moreover, an analog PID corrector is chosen for the FC current controller. As explained earlier that the fuel flows must be adjusted to match the reactant delivery rate to the usage rate, the FC current control loop is obligatory. So, the FC current reference  $i_{FCREF}$  is sent to the FC controller

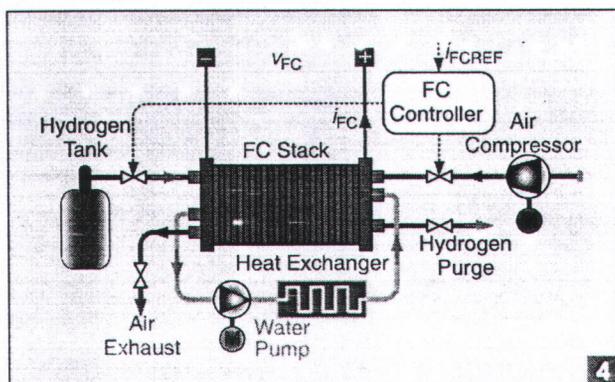
synchronously (refer to Figures 4 and 7). One can take advantage of the safety and high-dynamic characteristics of this loop as well; thus, it must be realized by analog circuits to function at high bandwidth.

The open-loop (OL) transfer function of an FC current regulation can be expressed as follows [23]:

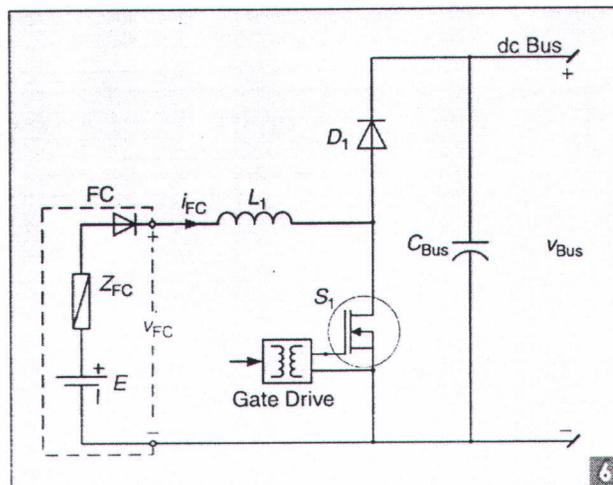
$$\left. \frac{\tilde{i}_{FCMea}(s)}{\tilde{i}_{FCREF}(s)} \right|_{OL} = G_C \frac{\overbrace{(T_{Ci}s + 1) \cdot (T_{Cd}s + 1)}^{\text{Analog PID controller}}}{T_{Ci}s} \cdot \underbrace{\frac{1}{V_P}}_{\text{PWM}} \cdot \underbrace{\frac{\tilde{i}_{FC}(s)/\tilde{d}(s)}{G_i(T_zs + 1)}}_{\text{filter}} \cdot \underbrace{\frac{1}{T_{FC}s + 1}}_{\text{filter}}$$

$$\text{with } \begin{cases} G_i = \frac{I_{FC}}{(1-D)} \\ T_z = \frac{V_{Bus} C_{Bus}}{(1-D)I_{FC}} \end{cases} \quad \text{and} \quad \begin{cases} \omega_n = \sqrt{\frac{(1-D)^2}{L_1 C_{Bus}}} \\ \zeta = \frac{R_{L_1} C_{Bus} \omega_n}{(1-D)^2} \end{cases} \quad (4)$$

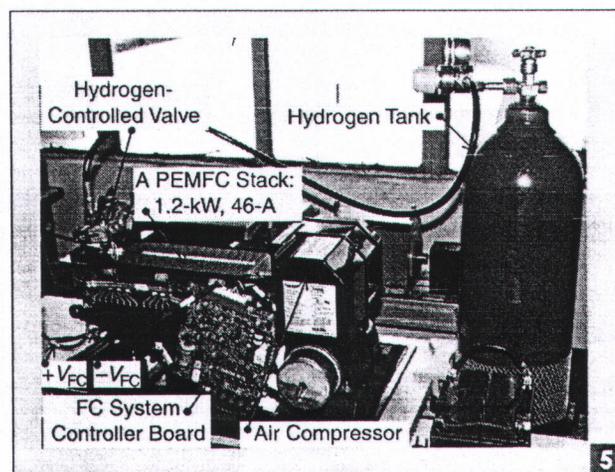
where  $D$  is the nominal duty cycle of the PWM FC converter,  $\tilde{d}$  is the duty cycle variations,  $V_P$  is the peak voltage of PWM carrier signal,  $V_{Bus}$  is the nominal dc bus voltage,  $I_{FC}$  is the nominal FC current,  $\tilde{i}_{FC}$  is the FC current variations, and  $R_{L_1}$  is the total series resistance of  $L_1$ , wiring, and FC.



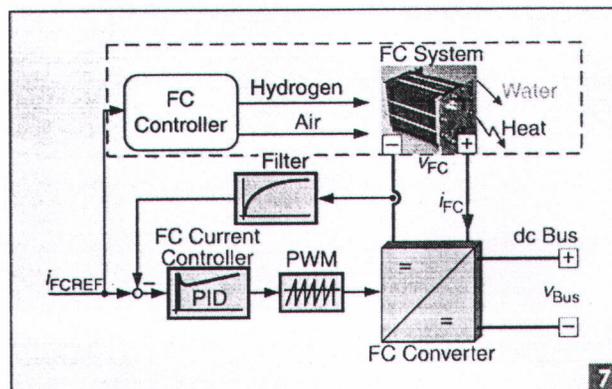
Simplified diagram of the PEMFC system.



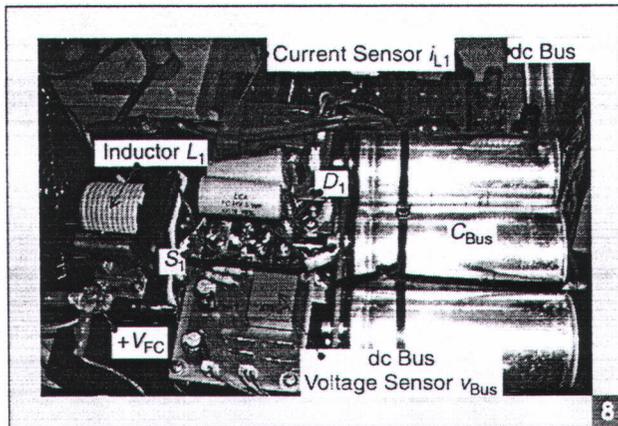
FC boost converter [23].



The Nexa PEMFC system (1.2 kW, 46 A, around 26 V), developed and commercialized by the Ballard Power Systems Inc., was used in our study.



FC current control loop [23].



Photograph of the FC converter (500 W) realized in the GREEN laboratory.

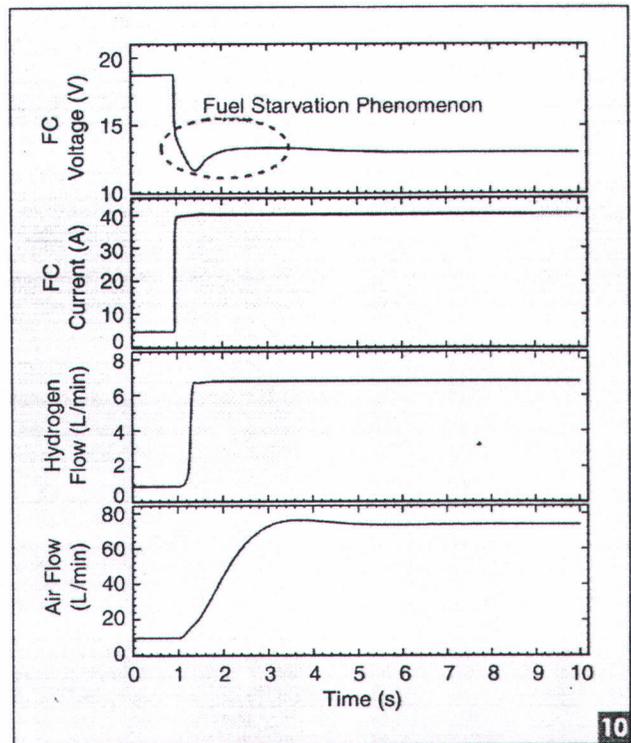
### Experimental Validation

#### Test Bench Description

The PEM FC system studied refers to Figures 2–4. Figures 8 and 9 show photographs of the test-bench system realized in the GREEN laboratory. The FC current reference comes from a digital-to-analog converter (ADCs) by a real-time-controller card dSPACE DS1104, through the mathematical environment of MATLAB-Simulink. For the FC converter (500 W) realized in the laboratory, the frequency of the PWM (by UC28025B-Texas Instruments Inc.) that drives the FC converter is 25 kHz. An inductor  $L_1$  is obtained by means of a ferrite core, and its inductance is 72  $\mu$ H. A total capacitance of  $C_{Bus}$  is 30 mF. A diode  $D_1$  is a STPS80H100TV Schottky rectifier (100 V, 40 A), and a switch  $S_1$  is STE180NE10 power MOSFET (100 V, 180 A) [14].

#### Fuel Starvation Phenomenon of an FC

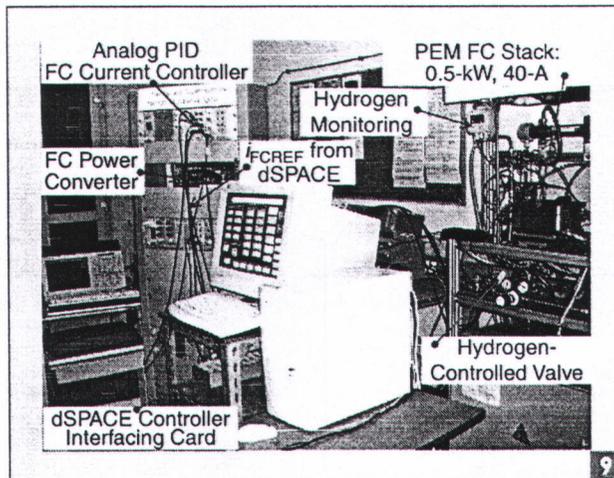
For clarity about the dynamic limitation of the FC generator, Figures 10 and 11 clearly present the PEM FC voltage response to a current. The tests operate in two different ways: current step and current slope. It shows the drop of the voltage curve in Figure 10, compared with Figure 11, because fuel flows (particularly the delay of air flow) have



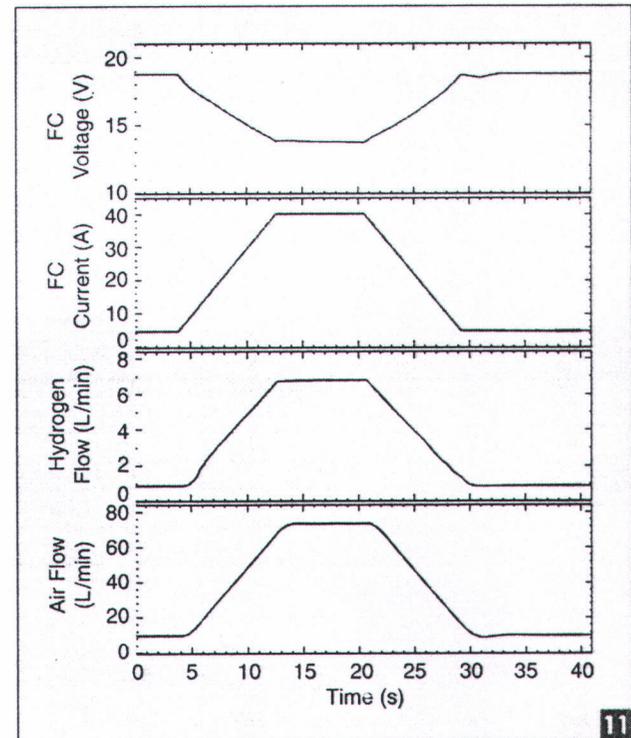
Fuel starvation phenomenon of the PEMFC to a high-current step from 5 A to 40 A (rate current).

difficulties following the current step, called the fuel starvation phenomenon.

Reliability and lifetime are the most essential considerations in such power sources. Previous research has clearly



Test-bench system.



FC dynamic characteristics to controlled current slope of 4 A · s<sup>-1</sup>.



demonstrated that hydrogen and oxygen starvation caused severe and permanent damage to the electrocatalyst of the FC, as well as reducing its performance of voltage-current curve. They have recommended that fuel starvation must absolutely be avoided, even if the operation under fuel starvation is momentary, in just 1 s [18].

Furthermore, at a steady state of 25 kHz switching frequency by means of the PWM, the characteristics of the FC ripple voltage and current are illustrated in Figure 12, in which the current references are 10 and 40 A (rated current), respectively. One can observe that its output impedance depends on operating point. One can also see the nonlinearity of the FC voltage curve during the change of current slope from positive to negative or vice versa. It can be concluded that an FC model is composed of complicated impedances [26], [27].

As illustrated in Figure 13, it also presents the worse case in which the FC system shuts down because of a high-

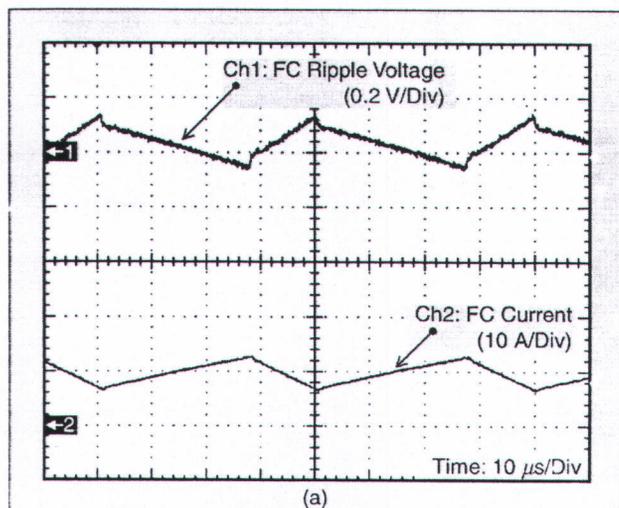
## FUEL OR OXIDANT STARVATION REFERS TO THE OPERATION OF FCs AT SUB-STOICHIOMETRIC REACTION CONDITIONS.

FC-voltage drop from the fuel starvation problem. As already explained earlier, after the FC system is operated in many times of fuel starvation, its performance is reduced.

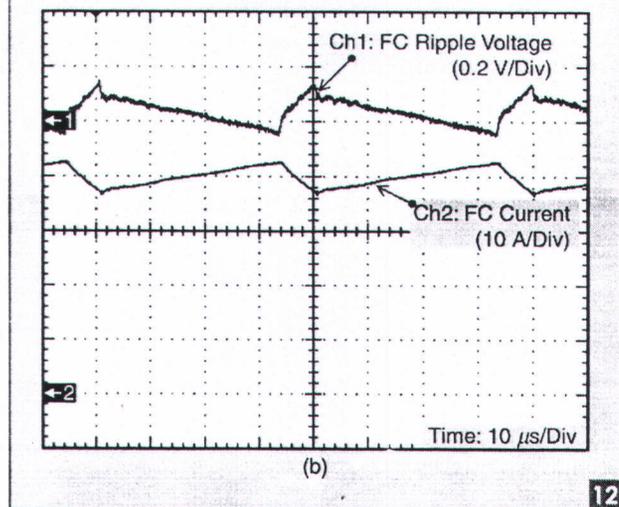
Without any doubt, to use the FC in dynamic applications, its current or power slope must be limited, but some research works have omitted to do this. One may lack the FC information in which failure modes for an FC are not well documented, degradation causes, and the mechanisms are not completely understood.

To solve this problem, the flow rate of oxygen and hydrogen is controlled continuously to follow the FC current variations by controlling the FC current slope as proposed in Figure 7, or by fixing a

constant fuel flow, for example, for the considered FC system set for 50 A. In this case, the FC has always enough fuel flows. Thus, no problem of FC starvation occurs as Figures 14–16

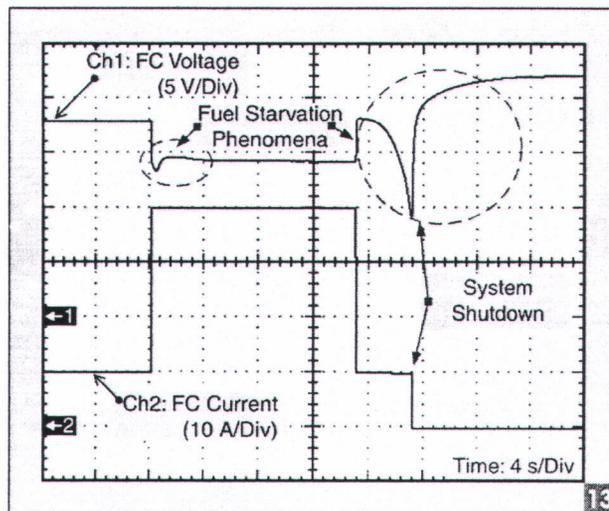


(a)

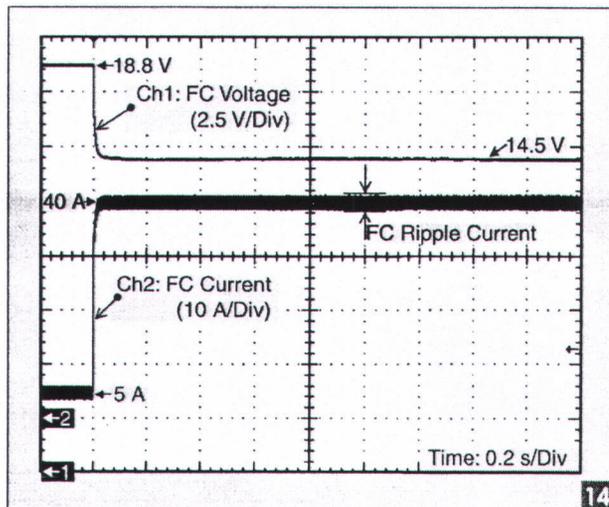


(b)

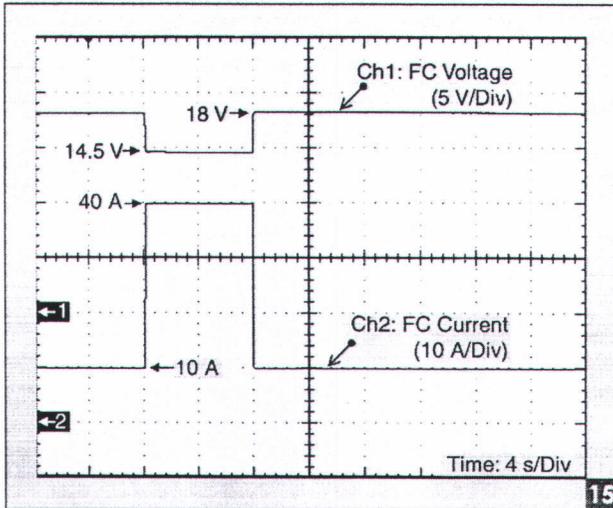
FC characteristics to a constant switching frequency at an FC current of (a) 10 A and (b) 40 A (rated current).



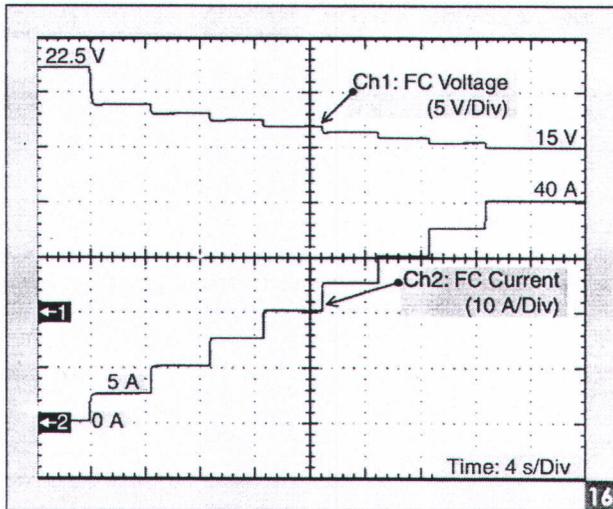
FC starvation problem.



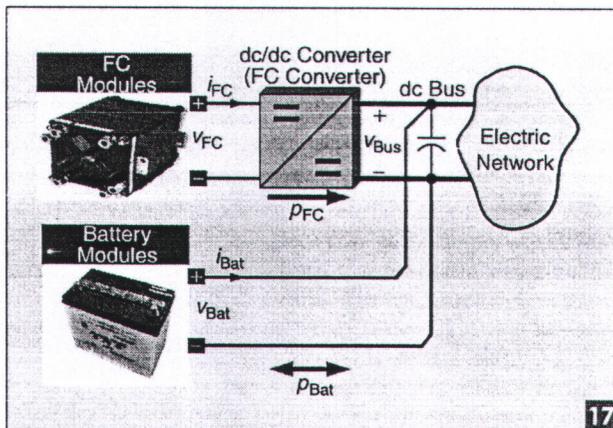
FC characteristics to a current step of 5–40 A (rated current) at a constant fuel flow (set for 50 A).



FC characteristics to a current step of 10–40 A (rated current) and vice versa at a constant fuel flow (set for 50 A).

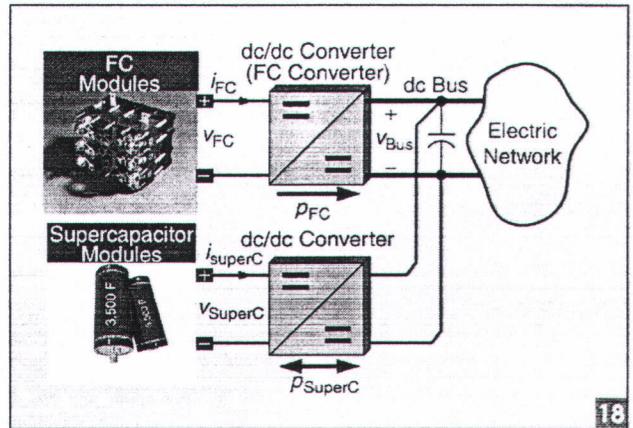


FC characteristics to a current step at a constant fuel flow (set for 50 A).

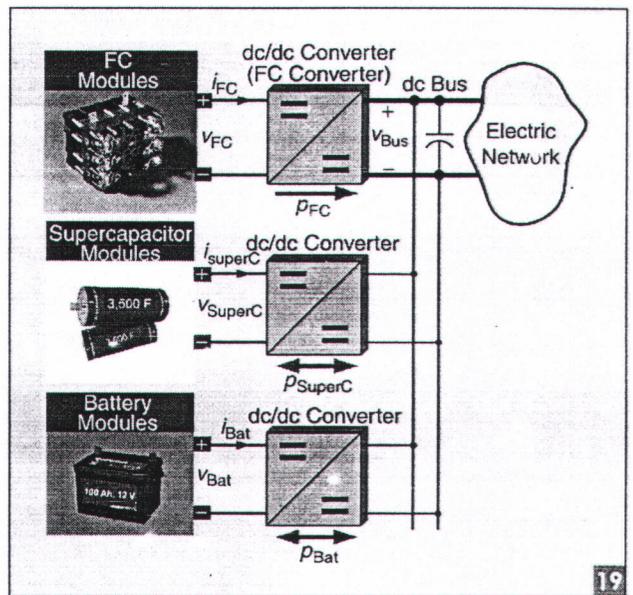


FC/battery hybrid power source [29]–[32].

portray. Nonetheless, this operating system has low efficiency because fuel flows (known as a power input of this generator) is always constant at a maximum value.



FC/supercapacitor hybrid power source [33]–[36].



FC/battery/supercapacitor hybrid power source [37].

Recent works with evidently experimental results have been based on the control of the FC current or power slope to meet a high-efficiency operation and to avoid the fuel starvation problem, for example,  $4 \text{ A} \cdot \text{s}^{-1}$  for a 0.5-kW, 12.5-V PEMFC [23]; and  $5 \text{ A} \cdot \text{s}^{-1}$ ,  $10 \text{ A} \cdot \text{s}^{-1}$  and  $50 \text{ A} \cdot \text{s}^{-1}$  for a 20-kW, 48 V PEMFC [28].

### Conclusions

The most important purpose of this work is to analyze the phenomenon of a fuel starvation of a PEM FC system. The incentive for automotive FC applications is quite different from that for stationary power generation or other applications. The dynamic characteristics of FC must be considered.

Experimental results based on a PEMFC (500 W, 40 A) noticeably substantiate that, to employ an FC in dynamic applications, its current or power slope must be limited to improve an FC performance, including its voltage–current curve and lifetime.

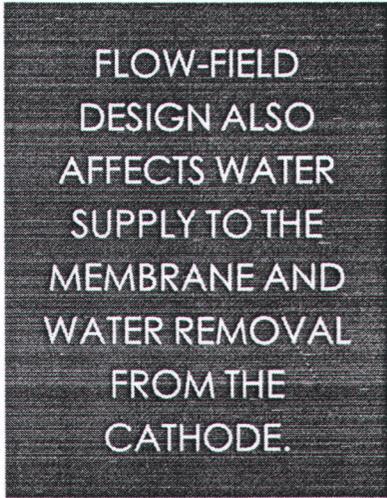
The use of other kinds of auxiliary power source(s) as depicted in Figures 17–19, such as batteries or supercapacitors to cooperate with FC main source, is mandatory for high dynamic applications, particularly for future FCVs.

## Acknowledgments

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## References

- [1] P. Thounthong, B. Davat, and S. Raël, "Drive friendly," *IEEE Power Energy Mag.*, vol. 6, no. 1, pp. 69–76, Jan./Feb. 2008.
- [2] S. Eccarius, F. Krause, C. Beard, and C. Agert, "Passively operated vapor-fed direct methanol fuel cells for portable applications," *J. Power Sources*, vol. 182, no. 2, pp. 565–579, Aug. 2008.
- [3] C. Kim, K. J. Kim, and M. Y. Ha, "Investigation of the characteristics of a stacked direct borohydride fuel cell for portable applications," *J. Power Sources*, vol. 180, no. 1, pp. 114–121, May 2008.
- [4] K. Rajashekara, J. Grieve, and D. Daggett, "Hybrid fuel cell power in aircraft," *IEEE Ind. Appl. Mag.*, vol. 14, no. 4, pp. 54–60, July–Aug. 2008.
- [5] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237–2245, June 2008.
- [6] S. Y. Choe, J. W. Ahn, J. G. Lee, and S. H. Baek, "Dynamic simulator for a PEM fuel cell system with a PWM dc/dc converter," *IEEE Trans. Energy Conversion*, vol. 23, no. 2, pp. 669–680, June 2008.
- [7] S. Jain and V. Agarwal, "An integrated hybrid power supply for distributed generation applications fed by nonconventional energy sources," *IEEE Trans. Energy Conversion*, vol. 23, no. 2, pp. 622–631, June 2008.
- [8] M. C. Pera, D. Candusso, D. Hissel, and J. M. Kauffmann, "Power generation by fuel cells," *IEEE Ind. Electron. Mag.*, vol. 1, no. 3, pp. 28–37, Fall 2007.
- [9] W. K. Na, B. Gou, and B. Diong, "Nonlinear control of PEM fuel cells by exact linearization," *IEEE Trans. Ind. Appl.*, vol. 43, no. 6, pp. 1426–1433, Nov./Dec. 2007.
- [10] G. Hoogers, *Fuel Cell Technology Handbook*. Boca Raton, FL: CRC Press, 2003.
- [11] S. Varigonda and M. Kamar, "Control of stationary and transportation fuel cell systems: Progress and opportunities," *Comput. Chem. Eng.*, vol. 30, no. 10–12, pp. 1735–1748, Sept. 2006.
- [12] R. von Helmolt and U. Eberle, "Fuel cell vehicles: Status 2007," *J. Power Sources*, vol. 165, no. 2, pp. 833–843, Mar. 2007.
- [13] D. Lecocq, "Tomorrow's energy today with Axane," *Fuel Cells Bull.*, vol. 2004, pp. 13–15, Mar. 2004.
- [14] P. Thounthong, S. Raël, and B. Davat, "Test of a PEM fuel cell with low voltage static converter," *J. Power Sources*, vol. 153, no. 1, pp. 145–150, Jan. 2006.
- [15] R. Gaynor, F. Mueller, F. Jabbari, and J. Brouwer, "On control concepts to prevent fuel starvation in solid oxide fuel cells," *J. Power Sources*, vol. 180, no. 1, pp. 330–342, 2008.
- [16] W. Schmittinger and A. Vahidi, "A review of the main parameters influencing long-term performance and durability of PEM fuel cells," *J. Power Sources*, vol. 180, no. 1, pp. 1–14, May 2008.
- [17] J. Wu, X. Z. Yuan, J. J. Martin, H. Wang, J. Zhang, J. Shen, S. Wu, and W. Merida, "A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies," *J. Power Sources*, vol. 184, no. 1, pp. 104–119, Sept. 2008.
- [18] A. Taniguchi, T. Akita, K. Yasuda, and Y. Miyazaki, "Analysis of electrocatalyst degradation in PEMFC caused by cell reversal during fuel starvation," *J. Power Sources*, vol. 130, no. 1–2, pp. 42–49, May 2004.
- [19] F. Grasser and A. Rufer, "A fully analytical PEM fuel cell system model for control applications," *IEEE Trans. Ind. Appl.*, vol. 43, no. 6, pp. 1499–1506, Nov./Dec. 2007.
- [20] W. K. Na and B. Gou, "Feedback-linearization-based nonlinear control for PEM fuel cells," *IEEE Trans. Energy Conversion*, vol. 23, no. 1, pp. 179–190, Mar. 2008.
- [21] K. P. Adzakpa, K. Agbossou, Y. Dubé, M. Dostie, M. Fournier, and A. Poulin, "PEM fuel cells modeling and analysis through current and voltage transient behaviors," *IEEE Trans. Energy Conversion*, vol. 23, no. 2, pp. 581–591, June 2008.
- [22] S. Pasricha, M. Keppler, S. R. Shaw, and M. H. Nehrir, "Comparison and identification of static electrical terminal fuel cell models," *IEEE Trans. Energy Conversion*, vol. 22, no. 3, pp. 746–754, Sept. 2007.
- [23] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle," *J. Power Sources*, vol. 158, no. 1, pp. 806–814, July 2006.
- [24] K. N. Reddy and V. Agarwal, "Utility-interactive hybrid distributed generation scheme with compensation feature," *IEEE Trans. Energy Conversion*, vol. 22, no. 3, pp. 666–673, Sept. 2007.
- [25] C. Wang and M. H. Nehrir, "Load transient mitigation for stand-alone fuel cell power generation systems," *IEEE Trans. Energy Conversion*, vol. 22, no. 4, pp. 864–872, Dec. 2007.
- [26] S. C. Page, A. H. Anbuky, S. P. Krumdieck, and J. Brouwer, "Test method and equivalent circuit modeling of a PEM fuel cell in a passive state," *IEEE Trans. Energy Conversion*, vol. 22, no. 3, pp. 764–773, Sept. 2007.
- [27] J. W. Jung and A. Keyhani, "Control of a fuel cell based Z-source converter," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, pp. 467–476, June 2007.
- [28] P. Corbo, F. Migliardini, and O. Veneri, "An experimental study of a PEM fuel cell power train for urban bus application," *J. Power Sources*, vol. 181, no. 2, pp. 363–370, July 2008.
- [29] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Conversion*, vol. 23, no. 1, pp. 148–155, Mar. 2008.
- [30] A. Kusko and J. DeDad, "Stored energy—Short-term and long-term energy storage methods," *IEEE Ind. Appl. Mag.*, vol. 13, no. 4, pp. 66–72, July–Aug. 2007.
- [31] S. K. Mazumder, S. K. Pradhan, J. Hartvigsen, M. R. von Spakovsky, and D. F. Rancruel, "Effects of battery buffering on the post-load-transient performance of a PSOC," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, pp. 457–466, June 2007.
- [32] Z. Jiang, L. Gao, and R. A. Dougal, "Adaptive control strategy for active power sharing in hybrid fuel cell/battery power sources," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, pp. 507–515, June 2007.
- [33] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell and supercapacitors association for a distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3225–3233, Dec. 2007.
- [34] M. Uzunoglu and M. S. Alam, "Modeling and analysis of an FC/UC hybrid vehicular power system using a novel-waveler-based load sharing algorithm," *IEEE Trans. Energy Conversion*, vol. 23, no. 1, pp. 263–272, Mar. 2008.
- [35] H. Tao, J. L. Duarte, and M. A. M. Hendrix, "Line-interactive UPS using a fuel cell as the primary source," *IEEE Trans. Ind. Electron.*, vol. 55, no. 8, pp. 3012–3021, Aug. 2008.
- [36] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2258–2267, June 2008.
- [37] H. Yoo, S. K. Sul, Y. Park, and J. Jeong, "System integration and power-flow management for a series hybrid electric vehicle using supercapacitors and batteries," *IEEE Trans. Ind. Appl.*, vol. 44, no. 1, pp. 108–114, Jan./Feb. 2008.



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## Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications

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### ABSTRACT

This paper proposes a perfect energy source supplied by a polymer electrolyte membrane fuel cell (PEMFC) as a main power source and storage devices: battery and supercapacitor, for modern distributed generation system, particularly for future fuel cell vehicle applications. The energy in hybrid system is balanced by the dc bus voltage regulation. A supercapacitor module, as a high dynamic and high power density device, functions for supplying energy to regulate a dc bus voltage. A battery module, as a high energy density device, operates for supplying energy to a supercapacitor bank to keep it charged. A FC, as a slowest dynamic source in this system, functions to supply energy to a battery bank in order to keep it charged. Therefore, there are three voltage control loops: dc bus voltage regulated by a supercapacitor bank, supercapacitor voltage regulated by a battery bank, and battery voltage regulated by a FC. To authenticate the proposed control algorithm, a hardware system in our laboratory is realized by analog circuits and numerical calculation by dSPACE. Experimental results with small-scale devices (a PEMFC: 500-W, 50-A; a battery bank: 68-Ah, 24-V; and a supercapacitor bank: 292-F, 30-V, 500-A) corroborate the excellent control principle during motor drive cycle.

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### 1. Introduction

High prices for gasoline and oil are here to stay. As China, India and other nations rapidly increase their demand for fossil fuels, future fighting over energy looms large. In the meantime, power plants that burn coal, oil and natural gas, as well as vehicles everywhere, continue to pour millions of tons of pollutants and greenhouse gases into the atmosphere annually, threatening the planet.

Well-meaning scientists, engineers, economists and politicians have proposed various steps that could slightly reduce fossil-fuel use and emissions. These steps are not enough. Therefore, this convinces us to dramatically change to hydrogen power, which would be the reasonable answer to this energy crisis problem.

Furthermore, beyond finding new alternative fuels for internal combustion engines (ICEs), researchers are working on hydrogen fuel cells that offer another path toward environmentally acceptable power [1–4]. To produce electricity, most PEM fuel cells must be supplied either with hydrogen or with hydrocarbon compounds that can be catalytically decomposed into hydrogen.

There are many types of FCs characterized by their electrolytes. One of the most promising ones to be utilized in electric vehicle applications is the polymer electrolyte membrane FC (PEMFC) because of its relatively small size, lightweight nature, and ease of construction [5,6]. In addition, PEMFC may also be used in residential and commercial power systems [7].

For the past 10 years, many works have been done on the utilizations of FCs in high power applications. Nowadays, the required FC power is in the range of 0.5-kW to 2-MW:

- 0.5-kW to 2-kW for unmanned aircrafts [8] and 40-kW to 700-kW for manned aircrafts [9,10];
- 50-kW to 100-kW for urban cars [11–14];
- 100-kW to 200-kW for buses and light tram [15–17];
- 600-kW to 1-MW for tramways and locomotives [18–20];
- 480-kW to 2-MW for distributed generation systems (grid parallel connection) [21–24].

The relatively short life of PEM fuel cells is a significant barrier to their commercialization in stationary and mobile applications. A longer life span for fuel cell components should be achieved to ensure high reliability, low maintenance costs and to justify fuel cells as economical alternative energy systems. Currently, the life-

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[phtt@kmutnb.ac.th](mailto:phtt@kmutnb.ac.th) (P. Thounthong).

time target requires PEM fuel cells to achieve 5000 h for mobile and 40,000 h for stationary applications [2].

The overall fuel cell performance decay rate, measured during continuous and uninterrupted operation, is the sum of both the stability and durability decay rates. Normal degradation targets require less than 10% loss in the efficiency of the fuel cell system at the end of life, and a degradation rate of  $2\text{--}10\ \mu\text{V h}^{-1}$  is typically accepted for most applications [2].

According to Thounthong et al. [25,26] experimented on a 0.5-kW PEMFC (ZSW Company, Germany) and a 1.2-kW Nexa™ PEMFC (Ballard Power System Company, Canada), Corrêa et al. [27] experimented on a 0.5-kW PEMFC (BCS Technology Company) and 0.5-kW PEMFC (Avista Company), Zhu et al. [28] experimented on a 0.5-kW PEMFC (Avista Company), Yoneyama et al. [29] experimented on a 100-kW PEMFC for railway vehicles, and Gaynor et al. [30] experimented on a 350-kW solid oxide FC, they point out the fact that the FC time constants are dominated by temperature and fuel delivery system (pumps, valves, and in some cases, a hydrogen reformer). As a result, fast energy demand will cause a high voltage drop in a short time, which is recognized as fuel starvation phenomenon [30,31]. Fuel or oxidant starvation refers to the operation of fuel cells at sub-stoichiometric reaction conditions. When starved from fuel or oxygen, the FC performance degrades and the cell voltage drops. This condition of operation is evidently hazardous for the FC stack [31,32].

Several factors can cause reactant starvation. A poor water management with flooding and a poor heat management during sub-zero temperatures and cold start-ups with ice within the cell can block the pores of the gas diffusion layers. A poor gas feeding management can lead to non-uniform distribution of the reactant gases resulting in partial or complete fuel and/or oxidant starvation or in sub-stoichiometric operation in individual cells, as already demonstrated in [32]. Reliability and lifetime are the most essential considerations in such power sources. Taniguchi et al. [32] clearly presented that hydrogen and oxygen starvation caused severe and permanent damage to the electro-catalyst of the fuel cell. They have recommended that fuel starvation must absolutely be avoided, even if the operation under fuel starvation is momentary, in just 1 s. In addition, an imperfect stack and cell design with an uneven distribution of mass in the flow fields, a poor stack assembly as well as quick load demands can be reasons contributing to gas starvation.

Thus, to utilize a FC in dynamic applications (such as in cars, tramways or trains), its current or power slope must be limited to circumvent the fuel starvation problem, for example,  $4\text{ A s}^{-1}$  for a 0.5-kW, 12.5-V PEMFC [33];  $2.5\text{ kW s}^{-1}$  for a 40-kW, 70-V PEMFC [34]; and  $5\text{ A s}^{-1}$ ,  $10\text{ A s}^{-1}$  and  $50\text{ A s}^{-1}$  for a 20-kW, 48 V PEMFC [35]. Then, the electrical system must have at least an auxiliary power source (energy storage device), such as battery or supercapacitor, to improve the system performance when electrical loads at a dc bus demand high power in a short time (for example, vehicle acceleration and deceleration).

To illustrate vehicle characteristics, Fig. 1 depicts a speed and power profile of a European urban tramway (weight: 40–60 tons) during a drive cycle for a 500-m course. The acceleration and deceleration of the vehicle is sustained by electric motor drives with large power. One can observe the following:

- The vehicle positive peak power is around 600, and the negative peak power is around  $-800\text{ kW}$ .
- The positive and negative peak power durations are around 15 s and 10 s, respectively.
- The average power is between 100 kW and 200 kW according to the auxiliaries (heating or air conditioning).
- The duration of drive cycle is 67 s.

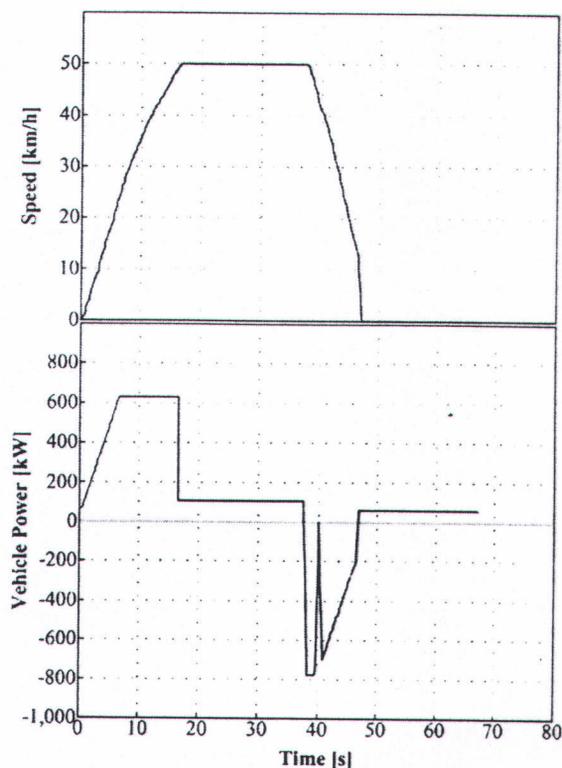


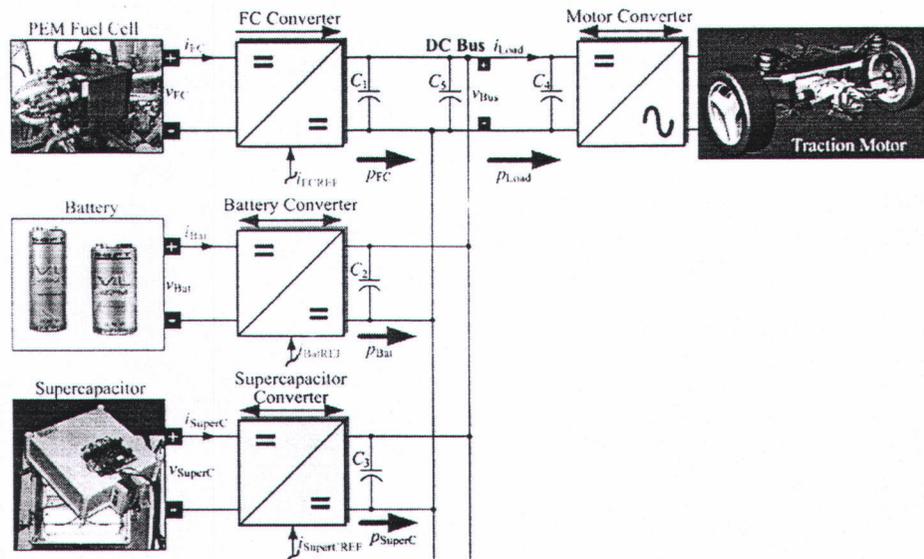
Fig. 1. Speed and power profile of a European urban tramway during a drive cycle for a 500-m course.

Thus, one can say that the drive cycle is with a high level of peak energy, a relative low average power, and duration around 67 s. Overall, the main power source operates most of the time at lower load. So, the hybridization consists in replacing the bulky generator of 600 kW, for example, with a smaller capable of providing the average power of 100 kW, and in coupling it with at least energy storage devices (typically batteries and supercapacitors) to provide the fluctuating power [36]. So, many recent works have already reported the structures of an FC/supercapacitor hybrid source [37,38] and an FC/battery hybrid source [39,40] for vehicle applications.

Energy storage technology is a main device in harvesting the kinetic energy that is wasted whenever vehicles or large machines must be slowed or stopped, called "regenerative braking energy". Although batteries have been successfully used in light-duty vehicles, hybrid platforms for trucks, buses, tramways and trains will require storage and delivery of much higher powers than can be accommodated readily by batteries. Unlike batteries, new technology storage device of electrochemical capacitors (ECs) can operate at high charge and discharge rates over an almost unlimited number of cycles [1] and enable energy recovery in heavier duty systems.

Like all capacitors, ECs (also called supercapacitors "SuperC" or ultracapacitors because of their extraordinarily high capacitance density) physically store charge. Conventional electrostatic and electrolytic capacitors store charge on low-surface-area plates, but supercapacitors store charge in an electric double layer set up by ions at the interface between a high-surface area carbon electrode and a liquid electrolyte. Supercapacitors first appeared on the market in 1978 as farad-sized devices to provide computer memory backup power [1].

The very high capacitance of supercapacitors comes at a cost. The operating voltage of a supercapacitor cell cannot exceed the potential at which the electrolyte undergoes chemical reactions (typically



**Fig. 2.** Proposed structure of fuel cell/battery/supercapacitor hybrid power source.  $P_{FC} (= V_{FC} \cdot i_{FC})$ ,  $V_{FC}$  and  $i_{FC}$  are the FC power, voltage, and current.  $P_{Bat} (= V_{Bat} \cdot i_{Bat})$ ,  $V_{Bat}$  and  $i_{Bat}$  are the battery power, voltage, and current.  $P_{SuperC} (= V_{SuperC} \cdot i_{SuperC})$ ,  $V_{SuperC}$  and  $i_{SuperC}$  are the supercapacitor power, voltage, and current.  $P_{Load} (= V_{Bus} \cdot i_{Load})$ ,  $V_{Bus}$  and  $i_{Load}$  are the load power, dc bus voltage, and load current, respectively.  $i_{FCREF}$ ,  $i_{BatREF}$ , and  $i_{SuperCREF}$  are the current reference signals for FC, battery, and supercapacitor current control loops, respectively.

2.5–3 V per cell). For high voltage applications, supercapacitor cells, like batteries, can be series-connected.

One of the most important advantages of batteries over supercapacitors is their high energy density. They can store 3–30 times more charge. However, supercapacitors can deliver hundreds to many thousands of times the power of a similar-sized battery. Besides, the highly reversible electrostatic charge storage in supercapacitors does not produce the changes in volume that usually accompany the redox reactions of the active masses in batteries. Such volume changes are the main cause of the limited cycle life of batteries (around 1000 cycles for a lead-acid battery), compared to demonstrated full charge–discharge cycles for supercapacitors into the many millions.

Presented here is a perfect hybridization of the batteries and supercapacitors as energy storage devices with a PEM fuel cell as a main source. It deals with the conception and the achievement of a regulated dc bus voltage hybrid power. Its interest is focused on an energy management in system, presented in Section 2. To authenticate the proposed hybrid structure, a small-scale hardware system is realized by analog circuits and numerical calculation (dSPACE). Experimental results in Section 3 will illustrate the system performances.

## 2. Fuel cell/battery/supercapacitor hybrid power source

### 2.1. Structure of hybrid power source

A series hybrid electric vehicle is a vehicle supplied by several electrical sources. The power bus is a dc link between sources and load. FCs produce dc voltage outputs, and they are always connected to electric power networks through power conditioning units such as dc/dc and dc/ac converters. Power conversion and control functions form the basis of what has come to be known as the field of power electronics. In recent years, power electronics technology has been spurred by needs for efficient control of industrial applications and the development of more reliable lightweight switching power supplies for sophisticated system.

Different power converter topologies can be used for the power electronic interface between the fuel cell and the utility dc bus. For the dc link voltage level, it is depending on its applications:

- 270 V or 350 V for the standard on the all-electric aircraft [41];
- 48 V, 120 V, or 400 V to 480 V for stand-alone or parallel grid connections [42];
- 42 V (PowerNet) [5];
- 270–540 V for electric (fuel cell) vehicles [5,43];
- 350 V (transit bus systems) to 750 V (tramway and locomotive systems) [17–20].

There are many possible structures to connect a main source and two storage devices with the utility dc bus. The total mass, volume, cost and efficiency (optimization) of the propulsion system are investigated. One of the good solutions is depicted in Fig. 2. It is composed of a unidirectional converter (step-up converter) for a FC stack, bidirectional (2-quadrant) converters for battery and supercapacitor modules. It is the most sufficient configuration when comparing mass, volume and cost, as detailed in [44,45].

For reasons of safety and dynamics, these converters are primarily controlled by inner current regulation loops, classically [33,40]. These current control loops are supplied by three reference signals:  $i_{SuperCREF}$ ,  $i_{BatREF}$ , and  $i_{FCREF}$ , generated by the energy management algorithm presented hereafter.

Note that the definitions of current direction are also illustrated in Fig. 2, and the dynamics of the current regulation loops are also supposed to be much faster than those of the outer voltage control loops, detailed hereafter. Thus, the currents  $i_{SuperC}$ ,  $i_{Bat}$ , and  $i_{FC}$  are considered to follow perfectly their references  $i_{SuperCREF}$ ,  $i_{BatREF}$ , and  $i_{FCREF}$ .

### 2.2. Energy management of hybrid power source

To manage the energy exchanges between the sources and the load at dc bus, three operating modes (or states) can be identified here again [33,40]:

- (1) Charge mode, in which the main source supplies energy to the storage devices and to the load.
- (2) Discharge mode, in which main source and storage devices supply energy to the load.
- (3) Recovery mode, in which the load supplies energy to the storage devices.

As mentioned earlier, FC has slow dynamics. It can be compensated by faster dynamics from storage devices. Batteries have the best energy density but a bad power density. Contrary to batteries, supercapacitors have lower energy density (1000 times lower) but higher power density (100 times higher) and provide very fast dynamic cycles (close to 1 ms) [1,37].

Furthermore, battery lifetime depends on many factors: the operating temperature; the number and the depth of discharge cycles; rate and eventually the amount and number of rest in a discharged state and overcharge. To optimize the lifetime of the batteries, it is advisable to limit the battery current slope in order to ensure a longer battery lifetime. On the other hand, supercapacitors can provide more cycles than batteries (virtually infinite cycles) and are well suited to very fast dynamic cycles [46–50].

The energy management strategy based on a dynamic classification, as portrayed in Fig. 3, aims at distributing the global power mission of the vehicle (refer to Fig. 1) into the sources in such a way that each source is optimally used. According to the three points mentioned above embedded energy sources can be classified as illustrated in Fig. 3. Note that the power unit in Fig. 3 is the normalized unit (or per-unit [pu]). So, the defined dynamic classification depicted in Fig. 3 is obtained from our simulation result. FC generator is controlled as the lowest dynamic power source. The FC current or power slope must be limited to avoid the fuel starvation problem. Normally, the FC limited current or power slope has been experimentally determined as the highest slope of operated FC system, where no fuel starvation occurs, for example,  $4 \text{ A s}^{-1}$  for a 0.5-kW, 12.5-V PEMFC [33]; and a  $2.5 \text{ kW s}^{-1}$  for a 40-kW, 70-V PEMFC [34]. Supercapacitor is the highest dynamic power source, which provides the micro-cycles and the fast dynamic power supply. Battery is between FC and supercapacitor in the dynamic classification.

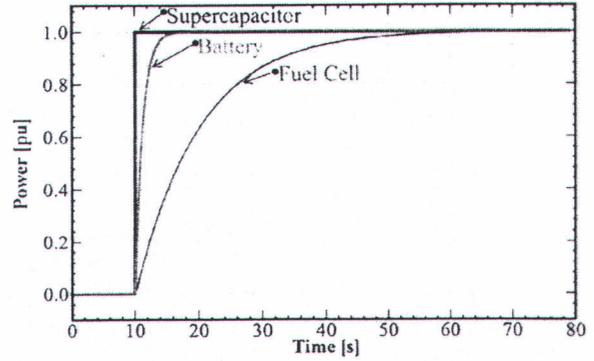


Fig. 3. Dynamic classification of the embedded sources.

Thounthong et al. [33,37] who studied a FC/supercapacitor hybrid source have proposed the hybrid energy management by regulating a dc bus voltage. Therefore, the proposed hybrid energy management here is shown in Fig. 4. Its basic principle here lies in using the supercapacitors (the fastest energy source), for supplying energy required to achieve the dc link voltage regulation. The batteries are controlled as the power source (with dynamic limitations,  $F_2$ ) that supplies energy to the supercapacitors to keep them charged. Then, the FC, although obviously the main energy source of the system, is functioned as the generator (with dynamic limitations,  $F_1$ ) that supplies energy to the batteries to keep them charged.

Consequently, the supercapacitor converter is driven to realize a classical dc bus voltage regulation. The battery converter is driven to maintain the supercapacitors at a given state-of-charge, here the

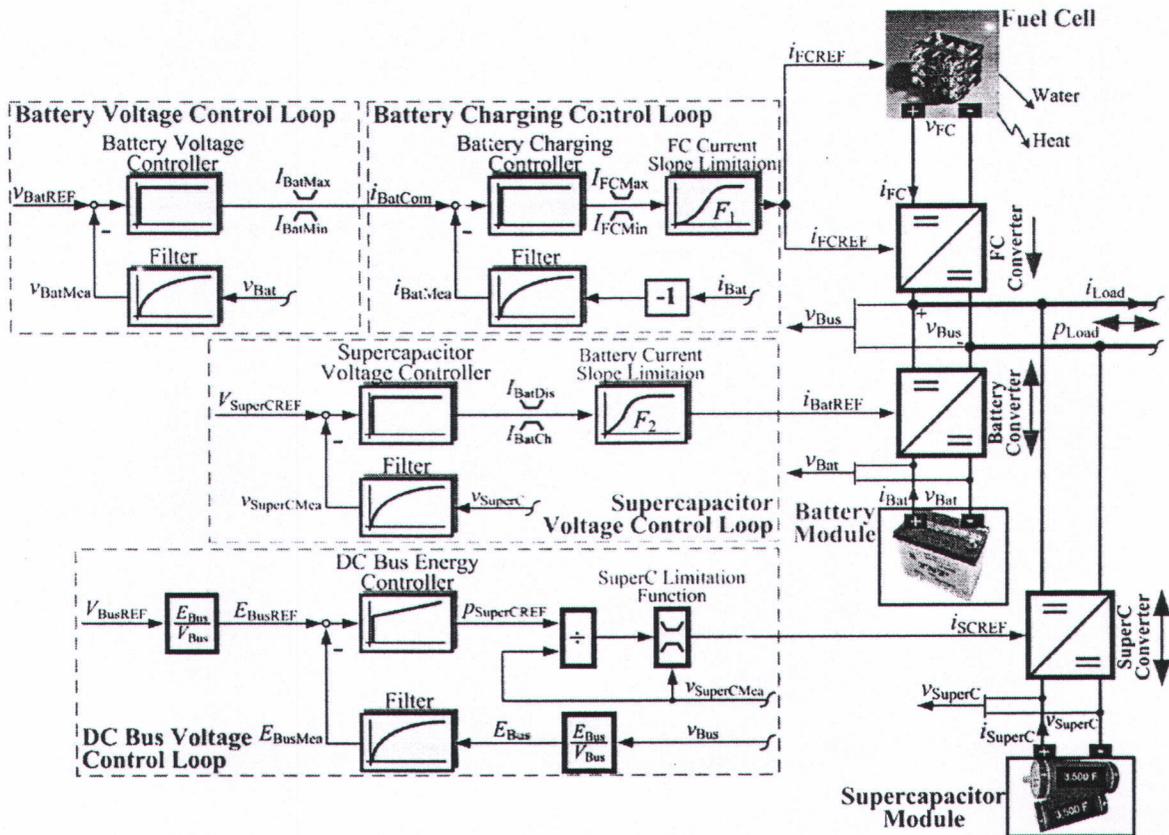


Fig. 4. Proposed energy management of the fuel cell/battery/supercapacitor hybrid power source.

supercapacitor voltage regulation. Then, the FC converter is also driven to maintain the batteries at a given state-of-charge, here the battery voltage regulation. As a result, the hybrid system composes of three-controlled variables:

- the dc bus voltage  $v_{Bus}$ ,
- the supercapacitor voltage  $v_{SuperC}$ , and
- the battery voltage  $v_{Bat}$ .

and three-control variables:

- the supercapacitor current reference  $i_{SuperCREF}$ ,
- the battery current reference  $i_{BatREF}$ , and
- the FC current reference  $i_{FCREF}$ .

As depicted in Fig. 2, one may write the classical power conservative law (without losses) of the FC/battery/supercapacitor hybrid power source as follow:

$$p_{Load}(t) = p_{SuperC}(t) + p_{Bat}(t) + p_{FC}(t) \tag{1}$$

where  $p_{Load}$  is the load power,  $p_{SuperC}$  is the supercapacitor power,  $p_{Bat}$  is the battery power, and  $p_{FC}$  is the fuel cell power.

2.2.1. DC bus voltage control loop

The dc bus voltage control loop considers a dc bus capacitive energy  $E_{Bus}$  as state variable, and the supercapacitor delivered power as command variable, to obtain a natural linear transfer function for the system [37]. If the losses in the FC, battery, and supercapacitor converters are neglected, the dc link capacitive energy is given versus supercapacitor power  $p_{SuperC}$ , battery power  $p_{Bat}$ , FC power  $p_{FC}$  and load power  $p_{Load}$  by the following differential equation:

$$\frac{dE_{Bus}(t)}{dt} = p_{SuperC}(t) + p_{Bat}(t) + p_{FC}(t) - p_{Load}(t) \tag{2}$$

which shows that the transfer function “ $E_{Bus}/p_{SC}$ ” is a pure integrator [37]. The dc bus energy measurement is carried out by means of the following classical calculation:

$$E_{Bus}(t) = \frac{1}{2} \cdot C_{Bus} \cdot v_{Bus}^2(t) \tag{3}$$

where  $C_{Bus}$  is the total capacitance of capacitors at the dc bus (refer to Fig. 2,  $C_{Bus} = C_1 + C_2 + C_3 + C_4 + C_5$ ). It enables the generation of both bus energy reference and bus energy measurement, through dc bus voltage reference  $v_{BusREF}$  and dc bus voltage  $v_{Bus}$ , respectively. Supercapacitor power reference  $p_{SuperCREF}$  is generated by means of a proportional–integral (PI)-controller. So, a first-order filter is used for  $E_{Bus}$  to reduce harmonics due to switching.  $p_{SuperCREF}$  is then divided by the measured supercapacitor voltage  $v_{SuperCMea}$ ,

and limited to maintain supercapacitor voltage within an interval  $[V_{SuperCMin}, V_{SuperCMax}]$ . The upper value  $V_{SuperCMax}$  of this interval corresponds to the maximum voltage of the storage device, and the lower value  $V_{SuperCMin}$ , traditionally equal to  $V_{SuperCMax}/2$ , to a level under which supercapacitor discharge becomes ineffective. This results in the supercapacitor current reference  $i_{SCREF}$ .

The supercapacitor current–voltage saturation function called “SuperC Limitation Function” as portrayed in Fig. 4, consists of limiting the reference  $i_{SuperCREF}$  to the interval [maximum charging current  $I_{SuperCMin}$  (negative value), maximum discharging current  $I_{SuperCMax}$  (positive value)] defined, versus the measured supercapacitor voltage  $v_{SuperCMea}$  as follows [33]:

$$\begin{cases} I_{SuperCMin} = -I_{SuperCRated} \cdot \min \left( 1, \frac{V_{SuperCMax} - V_{SuperCMea}}{\Delta v} \right) \\ I_{SuperCMax} = +I_{SuperCRated} \cdot \min \left( 1, \frac{V_{SuperCMea} - V_{SuperCMin}}{\Delta v} \right) \end{cases} \tag{4}$$

where,  $I_{SuperCRated}$  and  $\Delta v$  are the regulation parameters.

2.2.2. Supercapacitor voltage control loop

As presented in Fig. 4, a proportional (P)-controller is sufficient for the supercapacitor voltage control loop, as far as the proportional gain is high enough to introduce only a little static error. So, a first-order filter is used for supercapacitor voltage measurement, to reduce switching harmonics. The output signal from the regulator must be limited in level and slope, to respect constraints associated with the battery. Then the battery reference signal  $i_{BatREF}$  that drives the battery converter through the battery current control loop is then kept within an interval [maximum discharging current  $I_{BatDis}$  (positive value), maximum charging current  $I_{BatCh}$  (negative value)]. Moreover, the “Battery Current Slope Limitation” at a delay  $F_2$  enables safe operation of the battery, even during transient power demand. To obtain a natural linear transfer function, a second-order delay (filter)  $F_2$  is chosen for the battery current dynamics as follow:

$$F_2(s) = \frac{1}{(s/\omega_{n2})^2 + (2 \cdot \zeta_2/\omega_{n2})s + 1} \tag{5}$$

where  $\omega_{n2}$  and  $\zeta_2$  are the regulation parameters. So, a delay  $F_2$  of the battery dynamics must be faster than a delay  $F_1$  of the FC dynamics, refer to Figs. 3 and 4.

2.2.3. Battery voltage control loop

The proposed battery voltage control loop is also portrayed in Fig. 4. The simple method to charge the battery is the constant current–constant voltage (CCCV) charging as depicted in Fig. 5 [40], where  $Q_{Bat}$  is the battery capacity. The battery current is constant (maximum battery charging current  $I_{BatMax}$  is set around  $Q_{Bat}/5 - Q_{Bat}/10$ ; for a Li-ion battery, it can be set at  $I_{BatMax} = Q_{Bat}$ ) when the actual battery voltage  $v_{Bat}$  is far from the battery voltage reference  $v_{BatREF}$  and reduced current when  $v_{Bat}$  is near  $v_{BatREF}$  and zero when  $v_{Bat}$  is equal to  $v_{BatREF}$  (Fig. 5). Note here that a similar structure of the battery charging algorithm based on battery state-of-charge SOC has been reported in [40]. So, the main problem is that the battery capacity  $Q_{Bat}$  is not constant. It is dependent on many factors as follows [40]:

- the depth of discharge,
- discharge rate,
- cell temperature,
- charging regime,
- dwell time at low and high SOC,
- battery maintenance procedures,
- current ripple, and
- amount and frequency of overcharge.

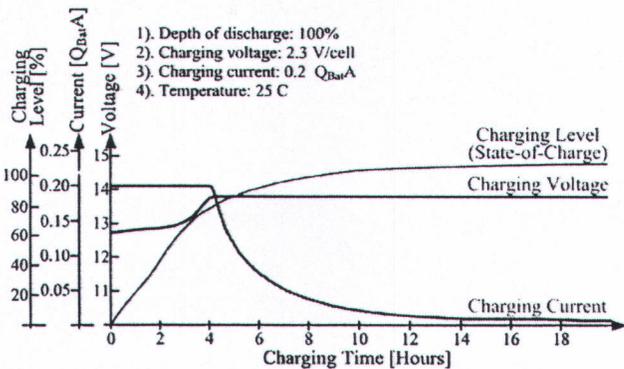


Fig. 5. Constant current–constant voltage charging of a lead-acid battery.

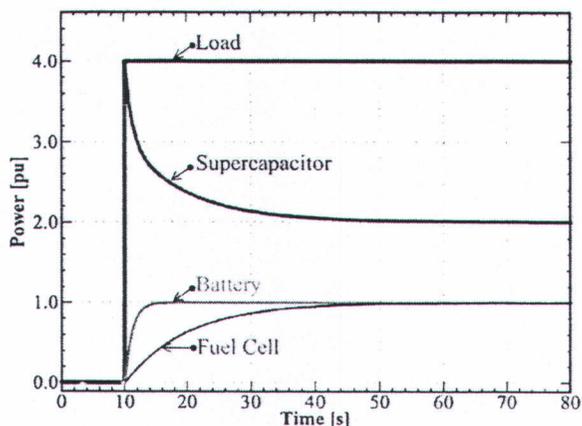


Fig. 6. Simulation result: hybrid source response during a high positive load step.

As a result, the battery voltage is here considered as a battery SOC. According to the proposed battery charging algorithm here, a P-controller is enough to generate a battery charging current. This signal must be limited within an interval [maximum charging current  $I_{BatMax}$  (equal to  $-1 \cdot I_{BatCh}$ ), maximum discharging current  $I_{BatMin}$  (equal to  $-1 \cdot I_{BatDis}$ ). The measured battery current must be inverted because the definition of battery current is negative for charging current.

2.2.4. Battery charging control loop

The battery charging control loop receives  $i_{BatCOM}$  from a battery voltage regulation loop as illustrated in Fig. 4. A P-controller is sufficient to generate the FC current reference  $i_{FCREF}$ . It must be limited in level, within an interval [maximum FC current  $I_{FCMax}$  (corresponding to a FC rated current), minimum FC current  $I_{FCMin}$  (set to 0A)] and limited in slope, which enables the safe operation of the FC in order to respect constraints associated with the FC, as far as the proportional gain is high enough to introduce only a small static error.

A first-order low-pass filter is used for the battery current measurement to reduce ripple current coming from the switching frequency. Moreover, the "FC Current Slope Limitation" at a delay  $F_1$  enables safe operation of the FC. To obtain a linear transfer function, a second-order delay (filter)  $F_1$  is also chosen for the FC current dynamics as:

$$F_1(s) = \frac{1}{(s/\omega_{n1})^2 + (2 \cdot \zeta_1/\omega_{n1})s + 1} \quad (6)$$

where  $\omega_{n1}$  and  $\zeta_1$  are the regulation parameters.

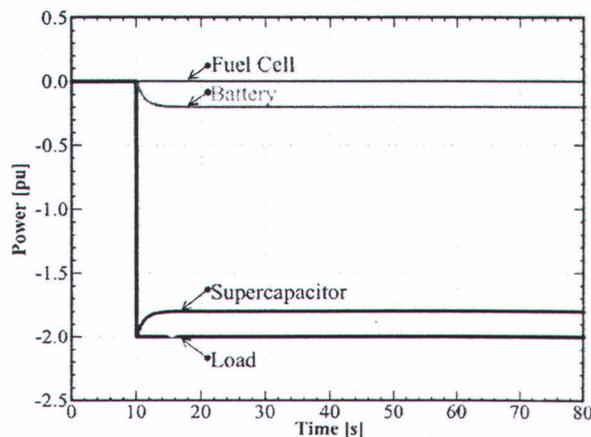


Fig. 7. Simulation result: Hybrid source response during a high negative load step (imitated regenerative braking).

2.2.5. Conclusion of proposed control algorithm

Using this form of control, the state of the supercapacitors is naturally defined, through the dc link voltage regulation, by the load power level and by its state-of-charge. In narrow steady-state conditions:

- (1) if load power is negative, the dc link voltage regulation generates a negative  $i_{SuperCREF}$ ;
- (2) if load power is positive greater than the approximate FC rated power summing with the battery rated power, the dc link voltage regulation generates a positive  $i_{SuperCREF}$ ;
- (3) otherwise, the state of the supercapacitors depends on its state-of-charge: supercapacitor current will therefore be positive if  $v_{SuperC} > V_{SuperCREF}$ , negative if  $v_{SuperC} < V_{SuperCREF}$ .

In all cases, battery state depends on supercapacitor voltage and its voltage. FC state depends only on battery voltage. The FC current will be strictly positive and less than  $I_{FCRated}$ . Otherwise it will be zero.

In transient conditions, as FC and battery power dynamics have been intentionally reduced by  $F_1$  and  $F_2$ , the supercapacitor supplies load variations. In effect, the dc bus voltage regulation transforms a sudden increase in load power into a sudden increase of supercapacitor current, and on the contrary a sudden decrease in load power into a sudden decrease of supercapacitor current.

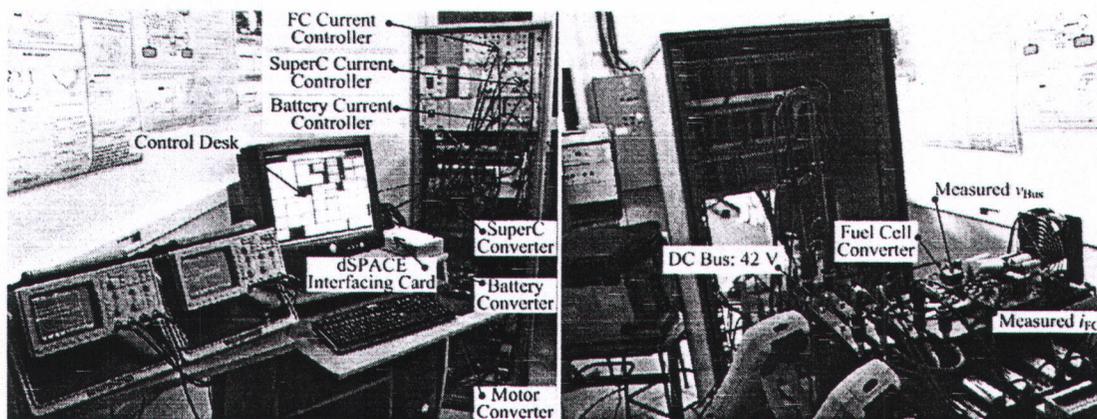


Fig. 8. Test bench of the fuel cell/battery/supercapacitor hybrid power source.

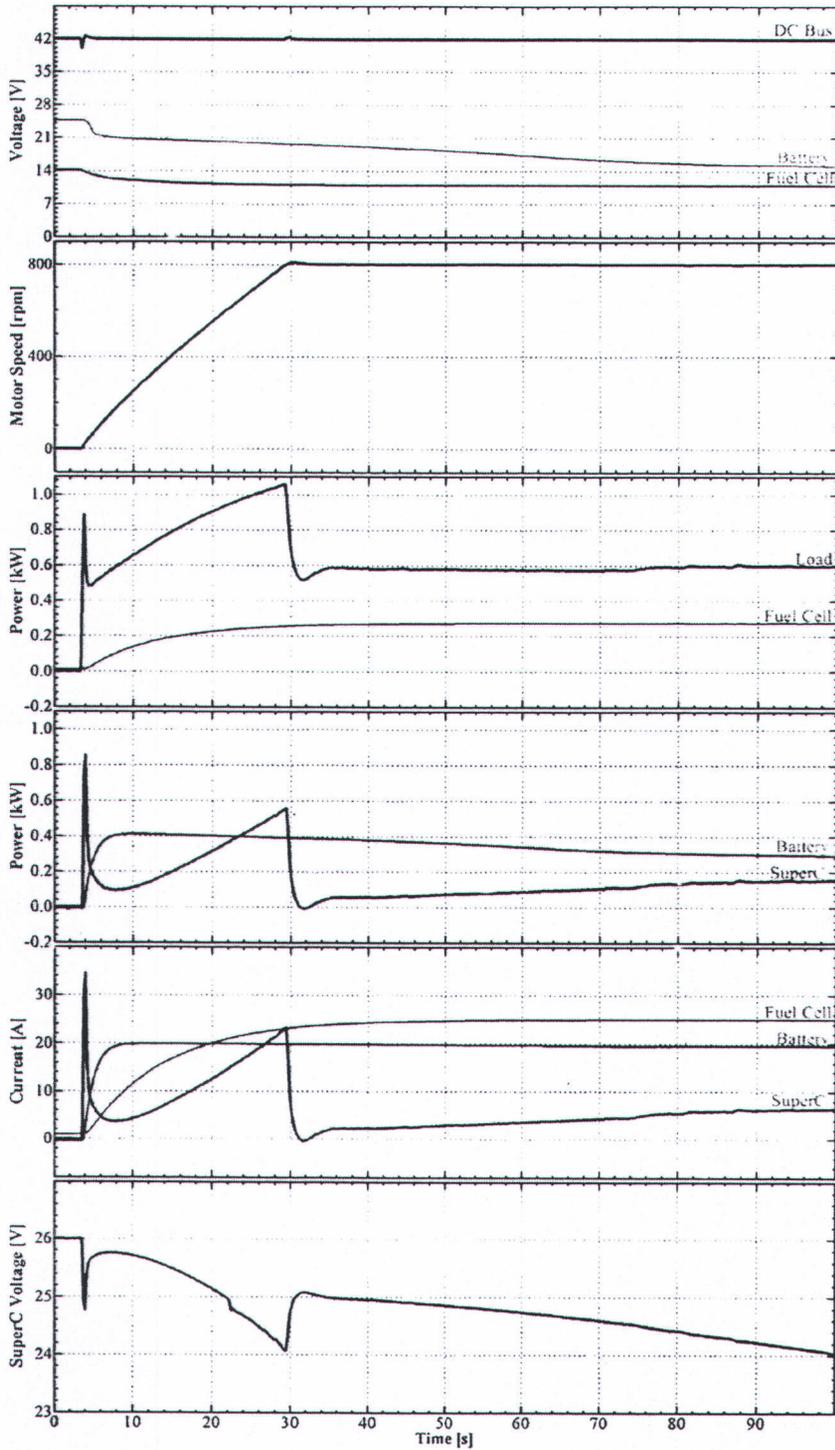


Fig. 9. Hybrid source response during motor starting to a final speed of 800 rpm.

Finally, Figs. 6 and 7 present simulation results during a high constant stepped load power. There are the load, supercapacitor, battery, and fuel cell power. In simulation, the FC minimum and maximum powers are set at 0.0 pu and 1.0 pu, respectively, and the battery minimum and maximum powers are set at -0.2 pu (corresponding to the maximum charging current) and 1.0 pu (corresponding to the maximum discharging current), respectively. As illustrated in Fig. 6, initially the supercapacitor and battery modules are full-of-charge, the load power is zero. As a result, the fuel

cell, battery, and supercapacitor powers are zero. At  $t=10$  s, the constant load power steps to 4.0 pu. One can observe the following:

- The supercapacitor module supplies most of the transient power required.
- The supercapacitor power is the fastest dynamics; the battery power is in the middle dynamics; then the FC power is the slowest dynamics.

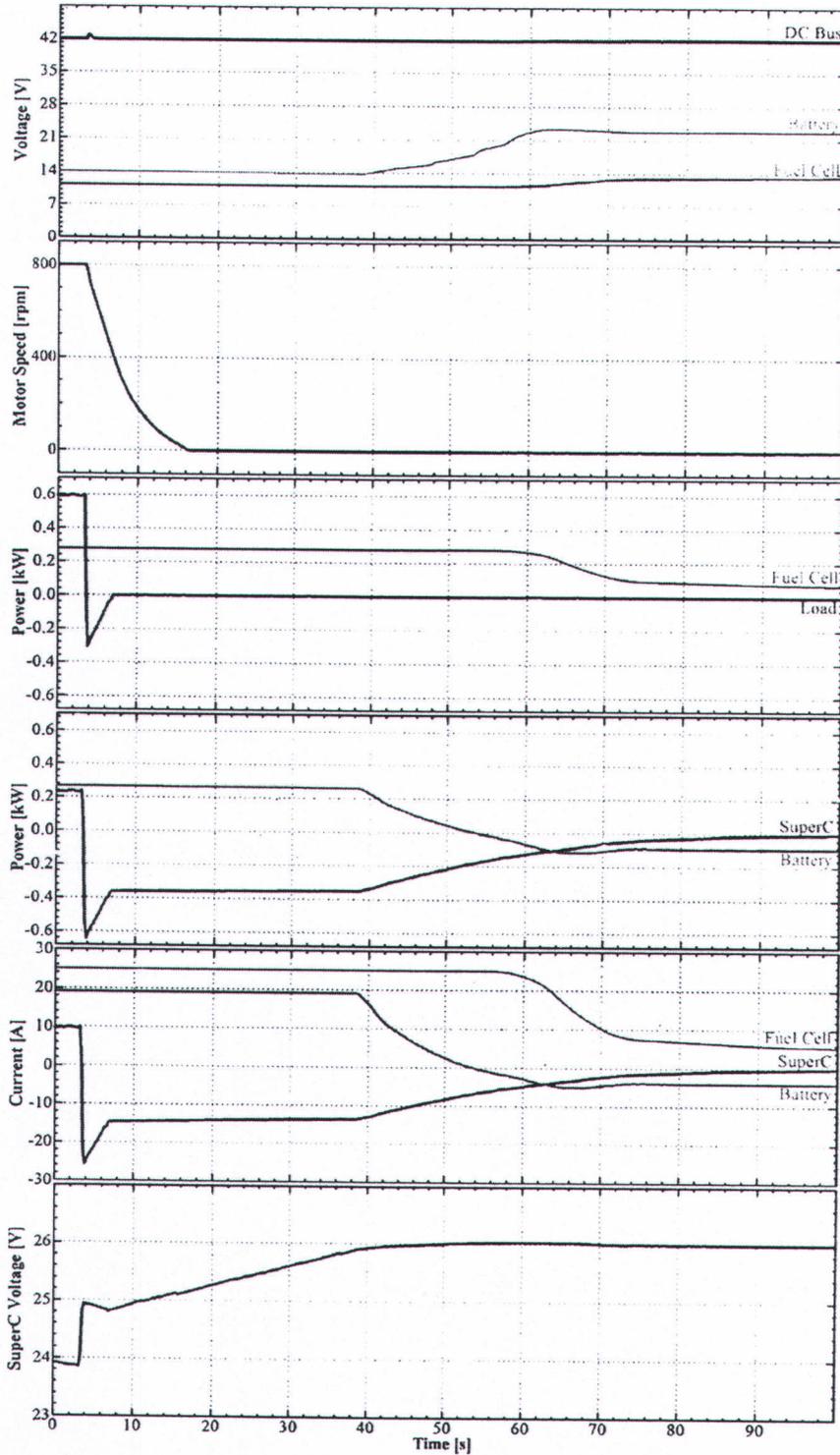


Fig. 10. Hybrid source response during motor braking from an initial speed of 800 rpm to stop.

- Synchronously, the supercapacitor power, after a sharp increase (discharging), decreases slowly to a constant discharge at 2.0 pu.
- At steady-state, the constant load power of 4.0 pu is entirely supplied by the FC of 1.0 pu, the battery of 1.0 pu (discharging state), and the supercapacitor of 2.0 pu (discharging state).

As a final simulation illustrated in Fig. 7, initially the supercapacitor and battery modules are full-of-charge, the load power is zero.

As a result, the fuel cell, battery, and supercapacitor powers are zero. At  $t = 10$  s, the constant load power steps to  $-2.0$  pu (imitated regenerative braking). One can see again the following:

- The supercapacitor module supplies most of the transient power required.
- The supercapacitor power is the fastest dynamics, and then following by the battery power.



- The FC power is still zero power, because the FC power source is a unidirectional power flow.
- Simultaneously, the supercapacitor power, after a sharp decrease (charging), increases slowly to a constant charge at  $-1.8$  pu.
- At steady-state, the constant regenerative braking power of  $-2.0$  pu is entirely absorbed by the battery of  $-0.2$  pu (charging state), and the supercapacitor power of  $-1.8$  pu (charging state).

### 3. Experimental validation

#### 3.1. Test bench description

A PEM fuel cell system (500 W, 50 A) studied here was constructed by the Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW) Company, Germany. It is composed of 16 cells in series with area of  $100 \text{ cm}^2$ . It is supplied with pure hydrogen from bottles under pressure and with clean, dry air from a compressor. Storage devices are obtained by means of two lead-acid batteries (68 Ah, 12 V) connected in series, and twelve supercapacitors (3500 F, 2.5 V, 500 A) developed and manufactured by the SAFT Company, France connected in series. In addition, a small-scale test bench in our laboratory is presented in Fig. 8.

The FC converter is a classical boost converter [25]. The battery and supercapacitor converters are bidirectional (2-quadrant) converters [33]. The load at dc link is only a traction motor drive of 2 kW coupled with a small-inertia flywheel.

The dc bus studied here is 42 V (PowerNet) [5]. For the supercapacitor, battery, and FC current control loops, they have been realized by analog circuits to function at high bandwidth. For the dc bus voltage, the supercapacitor voltage, the battery voltage, and the battery charging regulation loops have been implemented in the real time card dSPACE DS1104, through the mathematical environment of Matlab–Simulink, with a sampling frequency of 25 kHz. The ControlDesk™ software enables changes in the parameters of the control loops. The measurements of the dc bus voltage  $v_{\text{Bus}}$ , the supercapacitor voltage  $v_{\text{SuperC}}$ , supercapacitor current  $i_{\text{SuperC}}$ , the battery voltage  $v_{\text{Bat}}$ , the battery current  $i_{\text{Bat}}$ , and the FC current  $i_{\text{FC}}$  have been realized by means of zero-flux Hall effect sensors.

The voltage reference signals are set as follows:

- $V_{\text{BusREF}} = 42 \text{ V}$ ,
- $V_{\text{BatREF}} = 25 \text{ V}$ ,
- $V_{\text{SuperCREF}} = 26 \text{ V}$ .

For the minimum and maximum controlled parameters are set as follows:

- $i_{\text{SuperCRated}} = 200 \text{ A}$ ,
- $V_{\text{SuperCMin}} = 15 \text{ V}$ ,
- $V_{\text{SuperCMax}} = 30 \text{ V}$ ,
- $\Delta v = 0.5 \text{ V}$ ,
- $i_{\text{BatCh}} = -6 \text{ A}$ ,
- $i_{\text{BatDis}} = +20 \text{ A}$ ,
- $i_{\text{BatMax}} = 6 \text{ A}$ ,
- $i_{\text{BatMin}} = -20 \text{ A}$ ,
- $i_{\text{FCMin}} = 0 \text{ A}$ ,
- $i_{\text{FCMax}} = 25 \text{ A}$ .

Note here that for safety reasons the maximum FC current  $i_{\text{FCMax}}$  is set at 25 A (around 280 W) in place of 50 A (rated current).

#### 3.2. Experimental results

Figs. 9 and 10 portray waveforms obtained during a motor drive cycle. They present the dc bus, supercapacitor, battery, and FC

voltages; supercapacitor, battery, and FC currents; load (or approximately as a motor power), supercapacitor, battery, and FC powers; and motor speed.

As portrayed in Fig. 9, the initial state is zero for the load, supercapacitor, battery, and fuel cell powers. It means that the supercapacitor and battery modules are full of charge. One can observe the supercapacitor voltage is equal to the supercapacitor voltage reference of 26 V, and battery voltage is equal to the battery voltage reference of 25 V. At  $t = 4$  s, the motor starts to the final speed of 800 rpm, so that the steady-state load power supplies by the FC, battery, and supercapacitor sources. It can be observed the following:

- The supercapacitor module supplies most of the transient power required during motor acceleration.
- The supercapacitor power is the fastest dynamics; the battery power is in the middle dynamics; then the FC power is the slowest dynamics.
- Synchronously, the supercapacitor power, after a sharp increase (discharging) during motor acceleration, decreases slowly to a constant discharge at around 160 W.
- The steady-state load power is approximately 600 W, totally supplied by the FC, battery, and supercapacitor sources. The FC operates at a maximum current of 25 A, and the battery module is in the state of discharge with the constant discharging current  $i_{\text{BatDis}}$  of 20 A.

As a final test, Fig. 10 presents waveforms obtained at motor braking from an initial speed of 800 rpm to stop at  $t = 4$  s. One can scrutinize the regenerative braking energy from the traction motor supplies back to the dc bus, demonstrating four phases as follows:

- First, the supercapacitor recovers the energy supplied to the dc link by the FC, the battery, and the motor regenerative braking.
- Second, the FC supplies power for charging the supercapacitor and battery storage devices.
- Third, when the supercapacitor module is nearly full of charge, the FC power slowly reduces to charging only the battery module.
- Fourth, the supercapacitor module is full of charge ( $V_{\text{SuperCREF}} = v_{\text{SuperC}}$ ). Consequently, the FC supplies energy for only charging the battery.

Excellent, only little perturbations on the dc bus voltage can be seen during motor start/stop and the dynamics of FC and battery powers are reduced, which is of major importance in the proposed energy management hybrid power source.

### 4. Conclusions

The key objective of this present work is to propose an original control algorithm for a dc distributed generation supplied by a fuel cell main source, and the perfect storage devices: supercapacitors and batteries. The combined utilization of batteries and supercapacitors is the perfect hybridization system of a high energy and high power density. The study mainly focuses on the FC, battery and supercapacitor taking account of the intrinsic energetic characteristics of these sources (i.e. energy and power densities, typical operating dynamics) in the energy management strategy. Hence, the control principle presents how to stay away from the fast transition of the FC and battery powers, and then reducing the FC and battery stresses. As a result, hybrid power source will increase its lifetime.

Experimental results in our laboratory carried out using a small-scale test bench, which employs a PEMFC (500 W, 50 A), and storage devices composed of supercapacitor bank (292 F, 30 V) and

lead-acid battery module (68 Ah, 24 V), corroborate the excellent performances of the proposed energy management during a motor drive cycle. During motor starts/stops or other significant steps in load, the storage elements provide the balance of energy needed during the momentary load transition period; and also absorbs excess energy from regenerative braking.

### Acknowledgments

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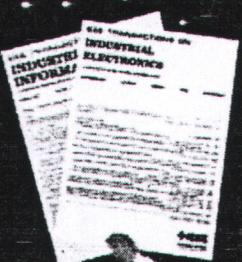
### References

- [1] P. Thounthong, B. Davat, S. Raël, *IEEE Power Energy* 6 (2008) 69–76.
- [2] W. Schmittinger, A. Vahidi, *J. Power Sources* 180 (2008) 1–14.
- [3] W.K. Na, B. Gou, *IEEE Trans. Energy Convers.* 23 (2008) 179–190.
- [4] M. Romer, G.H. Miley, N. Luo, R.J. Gimlin, *IEEE Trans. Energy Convers.* 23 (2008) 171–178.
- [5] A. Emadi, Y.J. Lee, K. Rajashekara, *IEEE Trans. Ind. Electron.* 55 (2008) 2237–2245.
- [6] K.P. Adzakpa, K. Agbossou, Y. Dubé, M. Dostie, M. Fournier, A. Poulin, *IEEE Trans. Energy Convers.* 23 (2008) 581–591.
- [7] M.C. Péra, D. Candusso, D. Hissel, J.M. Kauffmann, *IEEE Ind. Electron. Mag.* 1 (2007) 28–37.
- [8] T.H. Bradley, B.A. Moffitt, D.N. Mavris, D.E. Parekh, *J. Power Sources* 171 (2007) 793–801.
- [9] N.L. Rey, J. Mosquera, E. Bataller, F. Ort, C. Dudfield, A. Orsillo, *J. Power Sources* 181 (2008) 353–362.
- [10] K. Rajashekara, J. Grieve, D. Daggett, *IEEE Ind. Appl. Mag.* 14 (2008) 54–60.
- [11] R. von Helmolt, U. Eberle, *J. Power Sources* 165 (2007) 833–843.
- [12] T. Aicher, B. Lenz, F. Gschnell, U. Groos, F. Federici, L. Caprile, L. Parodi, *J. Power Sources* 154 (2006) 503–508.
- [13] R.M. Moore, K.H. Hauer, S. Ramaswamy, J.M. Cunningham, *J. Power Sources* 159 (2006) 1214–1230.
- [14] P. Fontela, A. Soria, J. Mielgo, J.F. Sierra, J. de Blas, L. Gauchia, J.M. Martinez, *J. Power Sources* 169 (2007) 184–193.
- [15] S. Varigonda, M. Kamat, *Comput. Chem. Eng.* 30 (2006) 1735–1748.
- [16] M. Saxe, A. Folkesson, P. Alvfors, *Energy* 33 (2008) 689–711.
- [17] M. Kim, Y.J. Sohn, W.Y. Lee, C.S. Kim, *J. Power Sources* 178 (2008) 706–710.
- [18] A.R. Miller, K.S. Hess, D.L. Barnes, T.L. Erickson, *J. Power Sources* 173 (2007) 935–942.
- [19] A.R. Miller, J. Peters, B.E. Smith, O.A. Velev, *J. Power Sources* 157 (2006) 855–861.
- [20] T. Ogawa, H. Yoshihara, S. Wakao, K. Kondo, M. Kondo, *Proceeding of the EPE 2007 – 12th European Conference on Power Electronics and Applications, Aalborg, Denmark, 2–5 September 2007*, pp. 1–8.
- [21] K.N. Reddy, V. Agarwal, *IEEE Trans. Energy Convers.* 22 (2007) 666–673.
- [22] M. Tekin, D. Hissel, M.C. Péra, J.M. Kauffmann, *IEEE Trans. Ind. Electron.* 54 (2007) 595–603.
- [23] J.W. Jung, A. Keyhani, *IEEE Trans. Energy Convers.* 22 (2007) 467–476.
- [24] C. Wang, M.H. Nehrir, *IEEE Trans. Energy Convers.* 22 (2007) 864–872.
- [25] P. Thounthong, S. Raël, B. Davat, *J. Power Sources* 153 (2006) 145–150.
- [26] P. Thounthong, P. Setnakul, S. Raël, B. Davat, *Proceedings of the 39th IEEE Power Electronics Specialists Conference (PESC), Island of Rhodes, Greece, 15–19 June, 2008*, pp. 230–236.
- [27] J.M. Corrêa, F.A. Farret, V.A. Popov, M.G. Simões, *IEEE Trans. Energy Convers.* 20 (2005) 211–218.
- [28] T. Zhu, S.R. Shaw, S.B. Leeb, *IEEE Trans. Energy Convers.* 21 (2006) 195–201.
- [29] T. Yoneyama, T. Yamamoto, K. Kondo, T. Furuya, K. Ogawa, *Proceeding of the EPE 2007 – 12th European Conference on Power Electronics and Applications, Aalborg, Denmark, 2–5 September 2007*, pp. 1–10.
- [30] R. Gaynor, F. Mueller, F. Jabbari, J. Brouwer, *J. Power Sources* 180 (2008) 330–342.
- [31] J. Wu, X.Z. Yuan, J.J. Martin, H. Wang, J. Zhang, J. Shena, S. Wu, W. Merida, *J. Power Sources* 184 (2008) 104–119.
- [32] A. Taniguchi, T. Akita, K. Yasuda, Y. Miyazaki, *J. Power Sources* 130 (2004) 42–49.
- [33] P. Thounthong, S. Raël, B. Davat, *J. Power Sources* 158 (2006) 806–814.
- [34] P. Rodatz, G. Paganelli, A. Sciarretta, L. Guzzella, *Control Eng. Pract.* 13 (2005) 41–53.
- [35] P. Corbo, F. Migliardini, O. Veneri, *J. Power Sources* 181 (2008) 363–370.
- [36] C. Wang, M.H. Nehrir, *IEEE Trans. Energy Convers.* 23 (2008) 957–967.
- [37] P. Thounthong, S. Raël, B. Davat, *IEEE Trans. Ind. Electron.* 54 (2007) 3225–3233.
- [38] M. Uzunoglu, M.S. Alam, *IEEE Trans. Energy Convers.* 23 (2008) 263–272.
- [39] Z. Jiang, L. Gao, R.A. Dougal, *IEEE Trans. Energy Convers.* 22 (2007) 507–515.
- [40] P. Thounthong, S. Raël, B. Davat, *IEEE Trans. Energy Convers.* 23 (2008) 148–155.
- [41] J. Dollmayer, N. Bundschuh, U.B. Carl, *Aerospace Sci. Technol.* 10 (2006) 686–694.
- [42] S.Y. Choe, J.W. Ahn, J.G. Lee, S.H. Baek, *IEEE Trans. Energy Convers.* 23 (2008) 669–680.
- [43] S.M. Lukic, J. Cao, R.C. Bansal, F. Rodriguez, A. Emadi, *IEEE Trans. Ind. Electron.* 55 (2008) 2258–2267.
- [44] E. Schaltz, S.J. Andreasen, P.O. Rasmussen, *Proceeding of the EPE 2007 – 12th European Conference on Power Electronics and Applications, Aalborg, Denmark, 2–5 September 2007*, pp. 1–10.
- [45] A. Stepanov, I. Galkin, L. Bisnieks, *Proceeding of the EPE 2007 – 12th European Conference on Power Electronics and Applications, Aalborg, Denmark, 2–5 September 2007*, pp. 1–7.
- [46] A. Kusko, J. Dedad, *IEEE Ind. Appl. Mag.* 13 (2007) 66–72.
- [47] S.K. Mazumder, S.K. Pradhan, J. Hartvigsen, *IEEE Trans. Energy Convers.* 22 (2007) 457–466.
- [48] H. Tao, J.L. Duarte, M.A.M. Hendrix, *IEEE Trans. Ind. Electron.* 55 (2008) 3012–3021.
- [49] J. Bauman, M. Kazerani, *IEEE Trans. Veh. Technol.* 57 (2008) 760–769.
- [50] T. Montanié, *Proceeding of the EPE 2003 – 10th European Conference on Power Electronics and Applications, Toulouse, France, 2–4 September 2003*, pp. 1–10.

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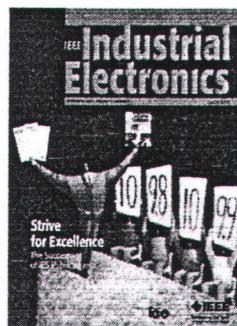
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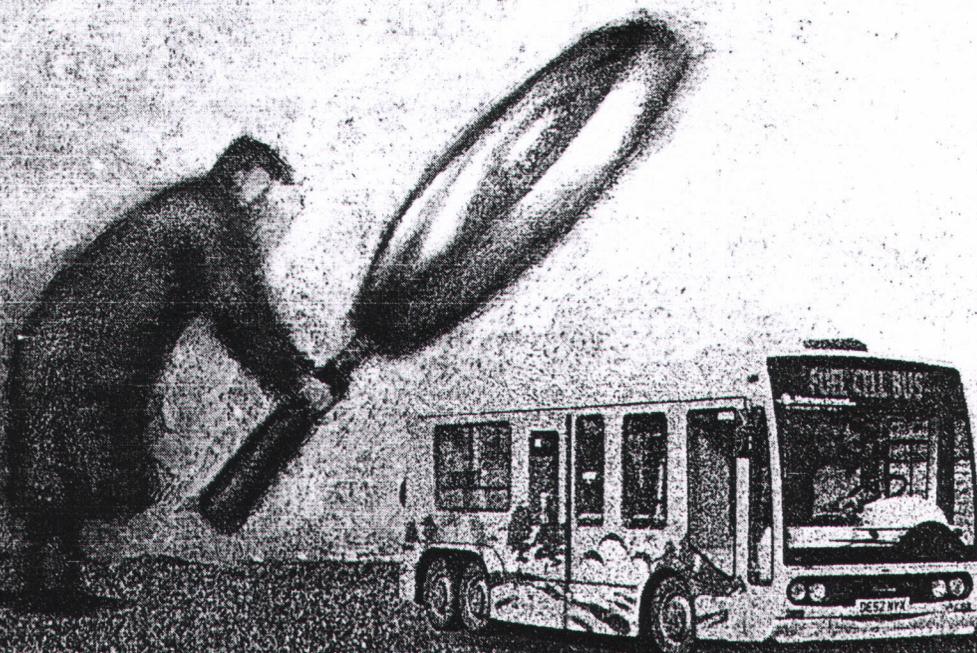
# The Benefits of Hybridization

*An Investigation of Fuel Cell/Battery and Fuel Cell/Supercapacitor Hybrid Sources for Vehicle Applications*

PHATIPHAT THOUNTHONG  
and STÉPHANE RAËL

**M**odern fuel-cell (FC) vehicles (such as cars, buses, trams, trains, or aircrafts) arose from an infusion of research money by several research agencies, including the U.S. Department of Energy (DOE) [1], [2], the Istituto Motori of Italian National Research Council (CNR) [3], the French National Center for Scientific Research (CNRS) [4], the French National Railways Company (SNCF), the ALSTOM Company [5], the Japan Railway Technical Research Institute [6]–[8], and so forth. The aim of this research is to study, analyze, and test energy-efficient and environmentally friendly traction systems.

FCs are able to generate electrical power with high-efficiency, low-operation noise, and no emissions from hydrogen or hydrogen-rich reformer gases and air. The byproducts are exhausted gases, water, and waste heat. The supplied electrical power can be used in vehicles for propulsion and operation of electrically powered



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accessories. Polymer electrolyte membrane FCs (PEMFCs) use a solid polymer electrolyte membrane, operate at lower temperature, and are considered most suitable for vehicle applications [9]–[12].

PEMFC systems require onboard stored hydrogen or hydrogen-rich gases generated onboard from liquid fuels, such as methanol, or the conventional hydrocarbons, gasoline and diesel. Because more advanced vehicles, such as the FC electric vehicle, have one energy storage (buffer) device as part of the propulsion system, it is possible and necessary to apply advanced control technologies to significantly optimize the vehicle's fuel economy, emissions, and drivability [13].

According to the recent works of Corrêa et al. [14], [15] (who worked with a 0.5-kW PEMFC by BCS Technology Company and 0.5-kW PEMFC by Avista Company), Thounthong et al. [16], [17] (who worked with a 0.5-kW PEMFC by Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW) Company and a 1.2-kW Nexa PEMFC by Ballard Power System Company), Zhu et al. [18] (who worked with a

0.5-kW PEMFC by Avista Company), Wang et al. [19] (who worked with a 0.5-kW PEMFC by Avista Company), and Gaynor et al. [20] (who worked with a 350-kW solid oxide FC), the FC time constants are dominated by temperature and fuel delivery system (pumps, valves, and, in some cases, a hydrogen reformer). As a result, fast energy demand will cause a high-voltage drop in a short time, which is recognized as fuel starvation phenomenon [21]–[23]. Fuel or oxidant starvation refers to the operation of FCs at substoichiometric reaction conditions. When starved from fuel or oxygen, the performance of the FC degrades, and the cell voltage drops. This condition of operation is evidently hazardous for the FC stack [24].

Therefore, to use an FC in dynamic applications, its current or power slope must be limited to circumvent the fuel starvation problem, e.g.,  $4 \text{ A} \cdot \text{s}^{-1}$  for a 0.5-kW, 12.5-V PEMFC [25] and  $5 \text{ A} \cdot \text{s}^{-1}$ ,  $10 \text{ A} \cdot \text{s}^{-1}$ , and  $50 \text{ A} \cdot \text{s}^{-1}$  for a 20-kW, 48-V PEMFC [26]. As a result, the vehicle electrical system must have at least an auxiliary power source (energy storage device), such as battery or

supercapacitor, to improve the performance of the system when electrical loads at a dc bus demand high power in a short time (e.g., vehicle acceleration and deceleration) [27], [28].

An FC vehicle can benefit from being hybridized with an energy storage device, which assumes some of the roles the FC would normally handle. It may increase fuel efficiency and improve the performance of the vehicle. Each energy storage type has advantages and disadvantages: a battery has lower power and high energy-storage capability; and a supercapacitor (ultracapacitor) has higher power but relatively low energy-storage capability. So, the energy storage systems in FC hybrid vehicles offer the well-known ability to [29], [30]

- absorb regenerative braking energy
- improve fuel economy
- provide a more flexible operating strategy
- overcome FC cold start and transient shortfalls
- potentially lower the cost per unit power.

This article presents the impact of the performance of an FC and control strategies on the benefits of hybridization. The possibilities to use a supercapacitor or battery bank as an auxiliary source with an FC main source are presented in detail. One considers that the storage devices are faster than an FC main source. Then, the storage device can complement the main source to produce the compatibility and performance characteristics needed in a load. The studies of two hybrid power systems for vehicle applications, FC/battery and FC/supercapacitor hybrid power sources, are explained. Experimental results with small-scale devices (a PEMFC of 500 W, 40 A, and 13 V; a lead-acid battery module of 33 Ah and 48 V; and a supercapacitor module of 292 F, 500 A, and 30 V) in laboratory will illustrate the performance of the system during motor-drive cycles.

### Conventional Power Train Architecture

For example, a modern European tram vehicle named modified Bombardier Transport sur Voie Réservee (TVR) is

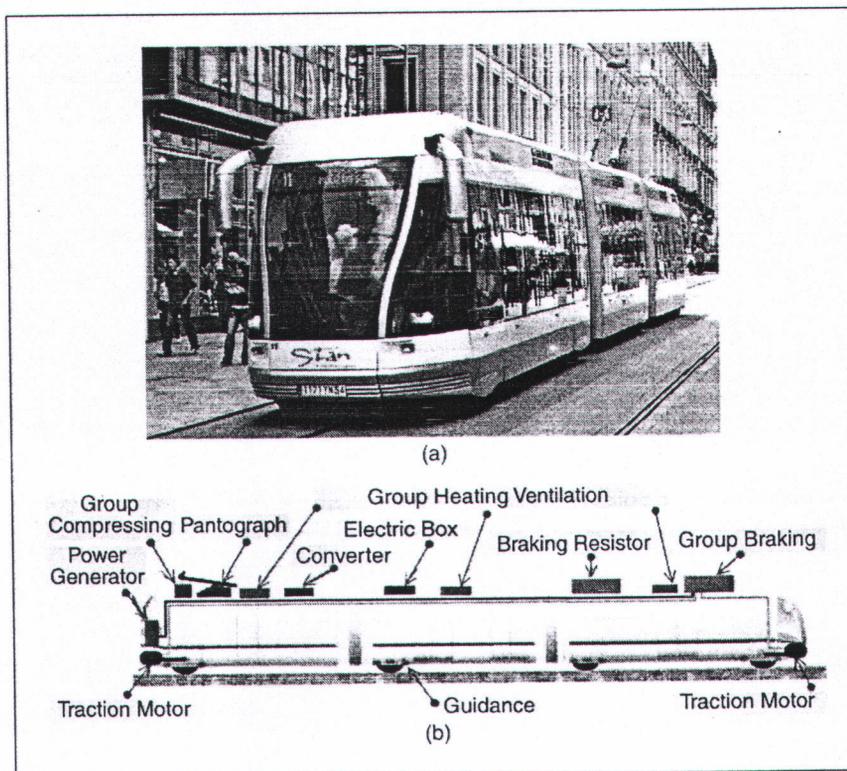


FIGURE 1 – Modern European tramway Bombardier TVR: (a) front view of the tramway in Nancy City Center, Lorraine, France, and (b) side view drawing of the three-car tramway.

presented in Figure 1. The front view of a rubber-tired vehicle in Nancy City Center, Lorraine, France, is given in Figure 1(a). The side view drawing of the three-car tramway is portrayed in Figure 1(b). The basic specifications of the vehicle are total weight (with six people/m<sup>2</sup>) = 38,000 kg, maximum mechanical power = 300 kW (2 × 150 kW), maximum speed = 70 km/h, and length = 25 m.

As depicted in Figure 2, the conventional power train of a tramway contains traction motors with their inverter and electronic loads, such as conditioning system and heating. The main electrical energy comes from the overhead contact line through the pantograph. This architecture allows the partial reuse of the regenerative braking energy of the vehicle if another vehicle is capable of using it. In this case, instead of burning it in the braking resistor, it is first used for the auxiliaries of the vehicle, and the complement is sent via the pantograph in the overhead contact line to another vehicle. To prevent high voltage at the dc bus, in case of control failure, or high energy during rapid braking of the traction motor when the storage device is fully charged, this structure must have a protection circuit by dissipating high energy in a braking resistor.

To illustrate vehicle characteristics, Figure 3 depicts the speed and power profiles of an European urban tramway during a drive cycle for a 500-m course. The acceleration and deceleration of the vehicle is sustained by motors and electric drives with large power. The characteristics of the vehicle are as follows:

- vehicle peak power is around 600 kW
- peak power duration is around 18 s (related to the slope)
- average power is between 100 and 200 kW according to the auxiliaries (heating or air conditioning)
- duration of standard cycle is between 67 and 80 s according to the slope

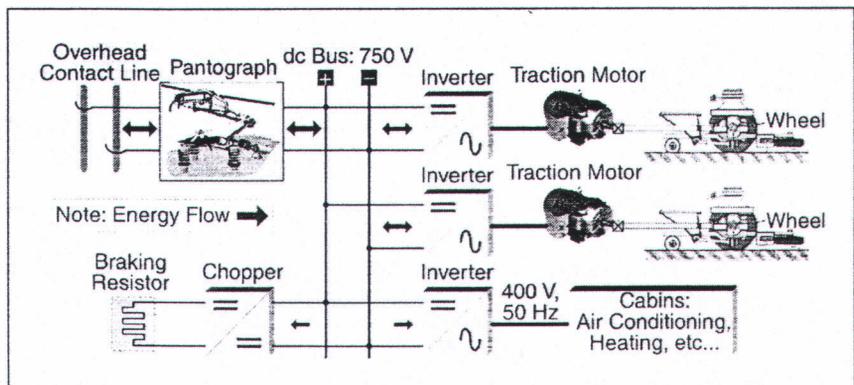


FIGURE 2—Schematic diagram of power-conventional tramway.

- negative peak power is -800 kW during around 10 s.

Therefore, the drive cycle is characterized by a great number of microcycles with a high level of peak energy, a relative low average power, and duration between 1 and 2 min. Overall, most of the time, the main power source operates at lower load. So, the hybridization consists of replacing the bulky generator of 600 kW with a smaller one of 100 kW capable of providing the average power. It is then coupled with at least one energy storage device (typically batteries or supercapacitors) to provide the peak

energy demanded and absorb the regenerative braking energy.

### Battery Versus Supercapacitor as an Energy Storage Device

The battery is still the most extensive energy storage device to provide and deliver electricity. Today, there are many kinds of battery technologies used, such as lead-acid, NiCd, NiMH, or Li ion. Using analytical expressions to model a battery behavior has always been limited by the complex nature of battery electrochemistry [31]–[33]. For lead-acid cell, the terminal voltage of battery  $V_b$  and internal resistance  $R_b$  are strong functions of the state of charge (SOC). The actual voltage curve is linear over most of its operating range; nevertheless, at the end of discharge, the voltage decreases very rapidly toward zero. This is because the internal resistance of a lead-acid battery is almost linear during discharge, but the losses are substantial below 25% SOC because of the increase in internal resistance of the battery. This is a reasonable work for the case of batteries used in electric vehicles, because the battery is typically operated only down to 60% SOC [or 40% depth of discharge (DOD), the amount of energy capacity that has been removed from a battery]. Usually, DOD is expressed as a percentage of the total battery capacity, and  $DOD = 100\% -$

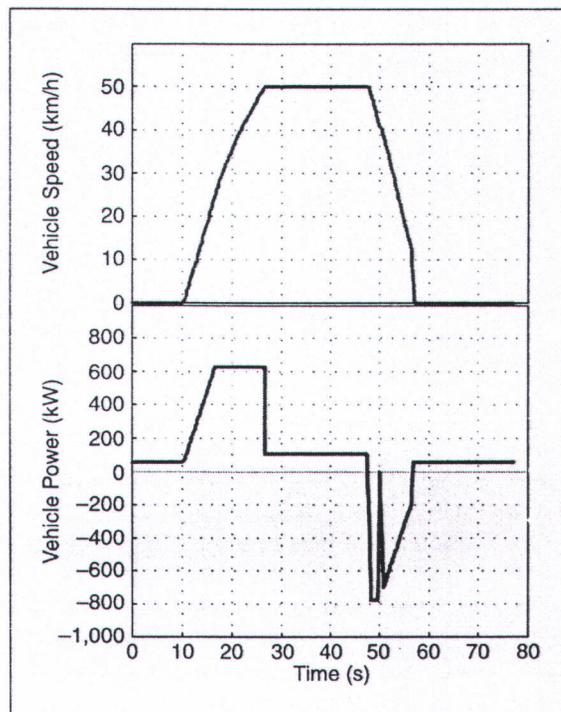


FIGURE 3—The speed and power profiles of an European urban tramway during a drive cycle.

SOC. So, the well-known battery SOC estimation is defined as [32], [33]

$$\text{SOC}(t) = \frac{1}{Q_{\text{Bat}}} \int_{t_0}^t i_{\text{Bat}}(\tau) d\tau + \text{SOC}_0(t_0), \quad (1)$$

where  $\text{SOC}_0$  is the known battery SOC (in percentages) at the time  $t_0$ ,  $Q_{\text{Bat}}$  is the rated capacity (Ah), and  $i_{\text{Bat}}(\tau)$  is the battery current (A).

Energy storage by supercapacitors is an emerging technology. Current breakthroughs in material design and fabrication methods aimed at maximizing rated capacitance have provided a tremendous increase in the energy storage capabilities of the supercapacitor [34], [35]. For example, an innovative prototype supercapacitor SC3500 model developed and manufactured by SAFT is 3,500 F, 2.5 V, 500 A, and 0.65 kg with a maximum energy storage capacity of 10,938 J ( $2 \text{ kW} \cdot \text{kg}^{-1}$  and  $4.67 \text{ Wh} \cdot \text{kg}^{-1}$ ) in an equivalent series resistance (ESR) of only 0.8 m $\Omega$  (representing small losses). Terminal voltage of the supercapacitor is limited, though, because of dissociation of the electrolyte. This limits the maximum voltage of 2.5–3 V.

When comparing the power characteristics of supercapacitors and batteries, the comparisons should be made for the same charge/discharge efficiency. Only one half of the energy at the peak power from the battery is in the form of electrical energy to the load, and the other one half is

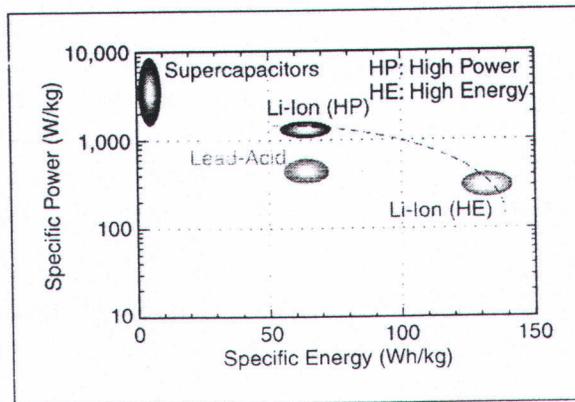


FIGURE 4—Specific power versus specific energy of modern storage devices: supercapacitor, lead-acid, and Li-ion battery technology. The supercapacitors and Li-ion batteries are based on the SAFT company.

dissipated within the battery as heat in the ESR. This is to say that the efficiency of batteries is around 50%. For supercapacitors, the peak power is usually for a 95% efficient discharge, in which only 5% of the energy from the device is dissipated as heat in the ESR. For a corresponding high-efficiency discharge, batteries would have a much lower power capability.

Furthermore, the main drawback of the batteries is a slow-charging time, limited by a charging current [36]; in contrast, the supercapacitors may be charged in a short time depending on a high-charging current (power) available from the main source. The capacitor voltage  $v_C$  can then be found using the following classical equation:

$$v_C(t) = \frac{1}{C} \int_{t_0}^t i_C(\tau) d\tau + v_C(t_0), \quad (2)$$

where  $i_C$  is the capacitor charging current.

Moreover, Figure 4 compares the advanced technologies of batteries and supercapacitors in terms of specific power and energy. Even though it is true that a battery has the largest energy density (meaning more energy is stored per weight than other technologies), it is important to consider the availability of that energy. This is the traditional advantage of capacitors. With a time constant of less than 0.1 s, energy can be taken from a capacitor at a very high rate [37]–[39]. On the contrary, the

same-size battery will not be able to supply the necessary energy in the same time. More advantageous, unlike batteries, supercapacitors can withstand a very large number of charge/discharge cycles without degradation (or visually infinite cycles) [11].

## FC/Battery and FC/Supercapacitor Hybrid Power Sources

### Structure of the Hybrid Power Sources

The FC operates giving dc and a low-dc voltage, and it is not current reversible; thereby, the step-up converter (called the FC converter) is always selected to adapt the low-dc voltage delivered by the FC to the utility dc-bus voltage [40]–[42].

The constraints to operate an FC are as follows:

- 1) The FC power or current must be kept within an interval (rated value, minimum value, or zero).
- 2) The FC current must be controlled as a unidirectional current.
- 3) The FC current slope must be limited to a maximum absolute value (e.g.,  $4 \text{ A} \cdot \text{s}^{-1}$  [25]) to prevent an FC stack from the fuel starvation phenomenon.
- 4) The switching frequency of the FC current must be greater than 1.25 kHz, and the FC ripple current must be lower than around 5% of rated value, to ensure minor impact to the FC conditions [43].

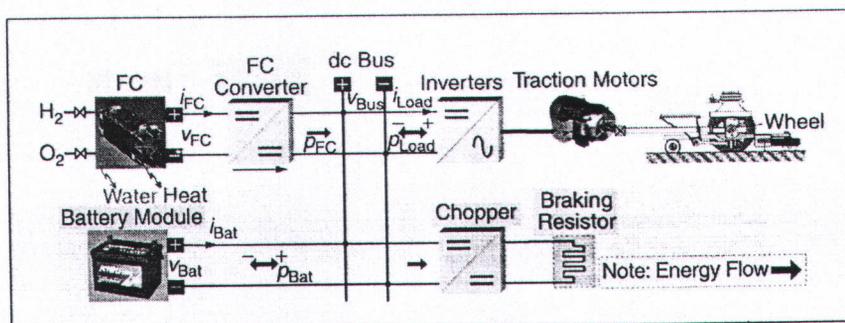


FIGURE 5—Concept of FC/battery hybrid power source, where  $p_{\text{FC}} (= v_{\text{FC}} \times i_{\text{FC}})$ ,  $v_{\text{FC}}$ , and  $i_{\text{FC}}$  are the FC power, voltage, and current, respectively.  $p_{\text{Bat}} (= v_{\text{Bat}} \times i_{\text{Bat}})$ ,  $v_{\text{Bat}}$ , and  $i_{\text{Bat}}$  are the battery power, voltage, and current, respectively.  $p_{\text{Load}} (= v_{\text{Bus}} \times i_{\text{Load}})$ ,  $v_{\text{Bus}}$ , and  $i_{\text{Load}}$  are the load power, dc-bus voltage, and load current, respectively.  $p_{\text{Load}} = p_{\text{FC}} + p_{\text{Bat}}$ . It has been assumed that there are no losses in FC converter, and here,  $v_{\text{Bus}}$  is  $v_{\text{Bat}}$ .

Concepts of the FC hybrid power sources are depicted in Figures 5 and 6. Because battery voltage, e.g., in a lead-acid battery, is nearly constant and virtually independent from discharge current and drops sharply when almost fully discharged, we propose the FC/battery hybrid source (Figure 5) by connecting the battery module directly to a dc bus [44], [45]. For the FC/supercapacitor hybrid source (Figure 6), the supercapacitor module is frequently connected to the dc bus using a classical two-quadrant (bidirectional) dc/dc converter [46], [47]. The supercapacitor current  $i_{\text{SuperC}}$ , which flows across the storage device, can be positive or negative, allowing energy to be transferred in both directions. The definitions of current direction are also illustrated in Figures 5 and 6.

### Energy Management of the Hybrid Power Sources

For reasons of safety and dynamics, the FC and supercapacitor converters are primarily controlled by inner current-regulation loops, classically. The dynamics of the current-regulation loops are also supposed to be much faster than those of the outer control loops, detailed hereafter. Therefore, the currents  $i_{\text{SuperC}}$  and  $i_{\text{FC}}$  are considered to follow perfectly their references  $i_{\text{SuperCREF}}$  and  $i_{\text{FCREF}}$ .

Besides, when an FC operates, its fuel (hydrogen and oxygen) flows are controlled by an FC controller, which receives current demand. This current demand is the FC current reference  $i_{\text{FCREF}}$  coming from the hybrid-control algorithms. The fuel flows must be adjusted to match the reactant delivery rate to the usage rate by an FC controller. For this reason, the inner FC current control loop is obligatory, and the hybrid-control algorithms demand energy from the FC to dc link by generating  $i_{\text{FCREF}}$  [48], which is sent to the FC system synchronously. One can take advantage of the safety and high-dynamic characteristics of this loop as well.

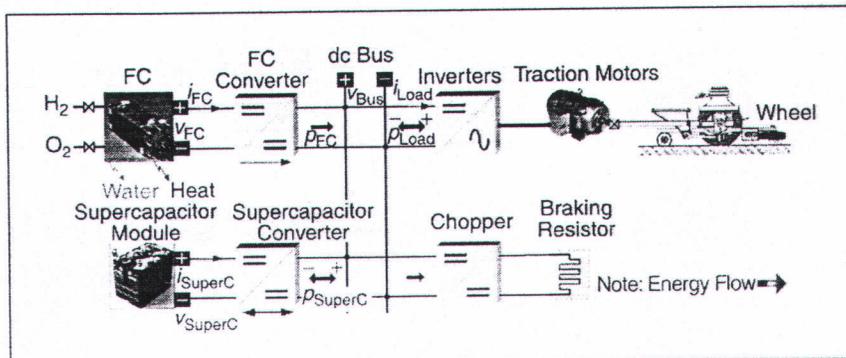


FIGURE 6—Concept of FC/supercapacitor hybrid power source, where  $p_{\text{FC}} (= v_{\text{FC}} \times i_{\text{FC}})$ ,  $v_{\text{FC}}$ , and  $i_{\text{FC}}$  are the FC power, voltage, and current, respectively.  $p_{\text{SuperC}} (= -v_{\text{SuperC}} \times i_{\text{SuperC}})$ ,  $v_{\text{SuperC}}$ , and  $i_{\text{SuperC}}$  are the supercapacitor power, voltage, and current, respectively.  $p_{\text{Load}} (= v_{\text{Bus}} \times i_{\text{Load}})$ ,  $v_{\text{Bus}}$ , and  $i_{\text{Load}}$  are the load power, dc-bus voltage, and load current, respectively.  $p_{\text{Load}} = p_{\text{FC}} + p_{\text{SuperC}}$ . It has been assumed that there are no losses in FC and supercapacitor converters.

To manage the energy exchanges among the loads in the hybrid system, the main source (here the FC), auxiliary source (the battery or supercapacitor), and three operating modes (or states) can be identified [11]:

- *Mode i*: charge mode, in which the main source supplies energy to the load and/or to the storage device (Figure 3; during 0–10 s, 26–46 s, and 56–80 s)
- *Mode ii*: discharge mode, in which both main source and storage device supply energy to the load (Figure 3; during 10–26 s)
- *Mode iii*: recovery mode, in which the load supplies energy to the storage device (Figure 3; during 46–56 s).

As mentioned earlier, the FC has slow dynamics. This can be compensated by faster dynamics from a storage device. The energy-management strategy based on a dynamic classification aims at distributing the global

power mission of the vehicle (Figure 3) into the sources in such a way that each source is optimally used. According to the dynamic characteristics of the hybrid power source mentioned earlier, embedded energy sources can be classified as illustrated in Figure 7. An FC generator is controlled as the lower dynamic power source. An auxiliary source is controlled as the higher dynamic power source, which provides the microcycles and fast dynamic power supply in the dynamic classification.

Therefore, the hybrid source-control strategies presented here intelligently lies in using the storage device, which is the fastest energy source of the system, for supplying the transient energy and absorbing the regenerative braking energy required by the load, as if this device were a standard power supply. In consequence, the FC may be seen as the generator that supplies energy to keep the storage device charged, although it is obviously the main energy source of the system.

### FC/Battery Hybrid Power Source

One takes advantage of a battery bank (which is directly connected to a dc bus for supplying transient energy demand and peak loads required during traction motor acceleration and deceleration) as if this device is a standard power

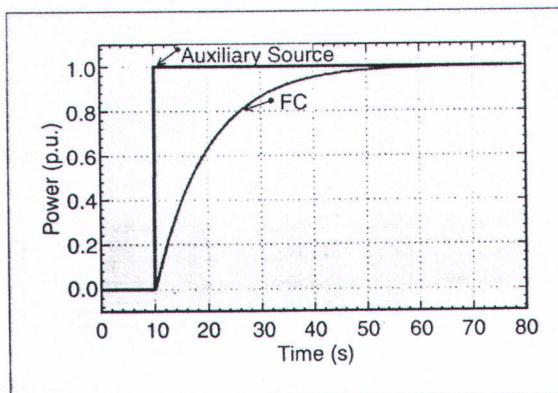


FIGURE 7—Dynamic classification of the FC hybrid power source (in p.u.).

supply. The proposed control strategy is a cascade-control structure composed of three loops as portrayed in Figure 8. The outer loop is the battery SOC control that links the battery SOC to the battery charging current reference  $i_{\text{BatREF}}$ . The middle loop controls the battery charging current and links  $i_{\text{BatREF}}$  to the FC current reference  $i_{\text{FCREF}}$ . The inner loop is the FC current control, which is not presented in Figure 8.

The simple method to charge the battery is constant current (maximum charging current  $I_{\text{BatMax}}$  is set around  $Q_{\text{Bat}}/10$ ; for a modern Li-ion battery, it can be set at  $I_{\text{BatMax}} = Q_{\text{Bat}}$ ) when the SOC is far from the SOC reference ( $\text{SOC}_{\text{REF}}$ ) and reduced current when the SOC is near  $\text{SOC}_{\text{REF}}$  and zero when the SOC is equal to  $\text{SOC}_{\text{REF}}$ . For the SOC, it can be estimated by using (1) as depicted in Figure 8 "Battery State-of-Charge Observer."

More importantly, in vehicle applications, battery monitoring is compulsory to replace aged batteries. In particular, the potential capacity  $Q_{\text{Bat}}$  is dependent on the DOD, discharge rate, cell temperature, charging regime, dwell time at low- and high-SOC, battery maintenance procedures, current ripple, and amount and frequency of overcharge [49].

It is beyond the scope of this work to observe the battery capacity. It is

assumed that  $Q_{\text{Bat}}$  is constant. Additionally, in a real system of applications,  $\text{SOC}_0$  [initial value of the battery SOC, (1)] can be retained in a storage device.

According to this SOC control algorithm, the battery SOC controller generates a battery charging current  $i_{\text{BatCh}}$  for the battery current-control loop, and the charging current must be limited at  $I_{\text{BatMax}}$ .

To avoid high voltage at the dc bus, in case of an erroneous SOC estimation or high regenerative braking, the dc-bus voltage (battery voltage) must be monitored to limit charging current. The battery current-limitation function consists of limiting the battery current reference  $i_{\text{BatREF}}$  versus the dc-bus voltage as

$$i_{\text{BatREF}}(t) = i_{\text{BatCh}}(t) \cdot \min\left(1, \frac{V_{\text{BusMax}} - v_{\text{Bus}}(t)}{\Delta v_{\text{Bus}}}\right), \quad (3)$$

where  $V_{\text{BusMax}}$  is the defined maximum dc-bus voltage, and  $\Delta v_{\text{Bus}}$  is the defined voltage band.

The battery current-control loop receives  $i_{\text{BatREF}}$  from an SOC regulation loop. The battery current controller generates the FC current reference  $i_{\text{FCREF}}$ . It must be limited in level, within an interval maximum  $I_{\text{FCMax}}$  (corresponding to a rated current of the FC) and minimum  $I_{\text{FCMin}}$  (set to 0 A) and limited in slope to

a maximum absolute value (in  $\text{A} \cdot \text{s}^{-1}$ ), which enables the safe operation of the FC to respect constraints associated with the FC.

One may summarize that the control principle of the whole system is based on the battery SOC, whatever the load power is.

- If the SOC is lower than  $\text{SOC}_{\text{REF}}$ , the battery charging current reference is negative value and an FC current is necessary to charge the battery.
- If the SOC is higher than  $\text{SOC}_{\text{REF}}$ , the battery charging current reference is positive value or equal to zero, and the FC current reference is reduced to zero.

As a consequence, a transient in the load modifies the FC current when the battery SOC becomes lower than the  $\text{SOC}_{\text{REF}}$ . In any case, if SOC is higher than  $\text{SOC}_{\text{REF}}$ , the FC current reference is equal to zero. For transient conditions, as FC current dynamics have been intentionally reduced, the battery supplies all load variations.

### FC/Supercapacitor Hybrid Power Source

To manage energy exchange in the system, its basic principle lies in using the supercapacitor, which is the fastest energy source of the system, for supplying the energy required to achieve the dc-bus voltage regulation,

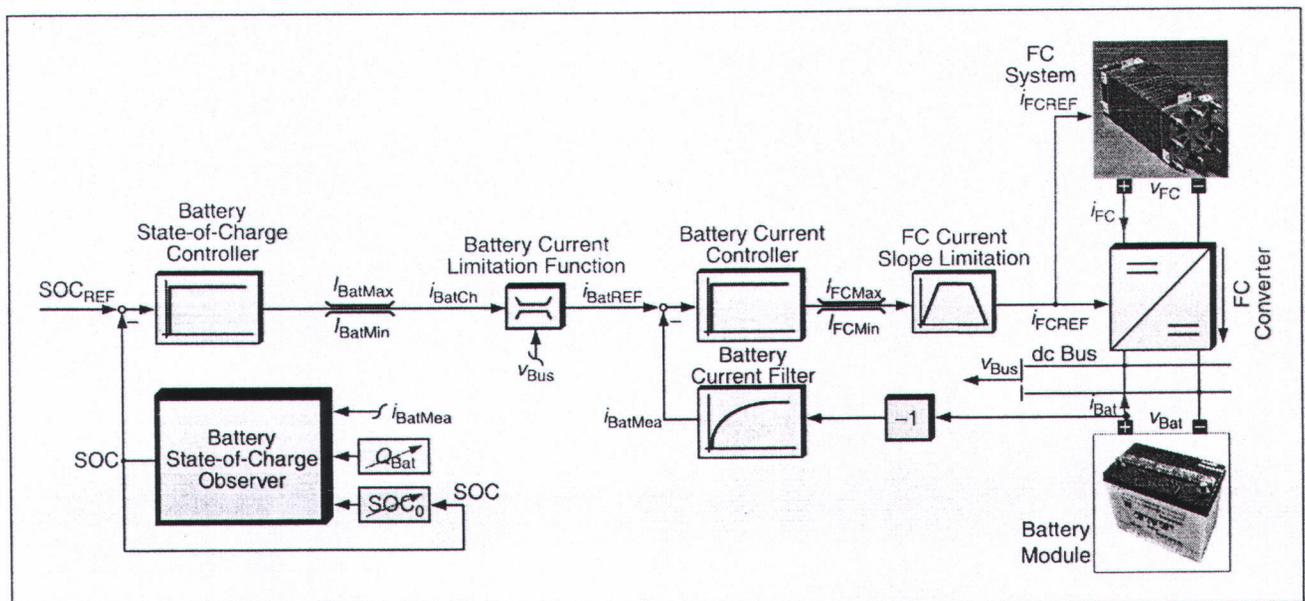


FIGURE 8—Proposed energy management of the FC/battery hybrid power source [49].

as if this device were a standard power supply. Therefore, the FC, although obviously the main energy source of the system, is operated for supplying energy to supercapacitors to keep them charged [50], [51].

Consequently, the supercapacitor converter is driven to realize a classical dc-bus voltage regulation, and the FC converter is driven to maintain the supercapacitor module at a given SOC. The supercapacitor and FC current-control loops are supplied by two reference signals,  $i_{\text{SuperCREF}}$  and  $i_{\text{FCREF}}$ , generated by the dc-bus voltage-regulation loop and supercapacitor voltage-regulation loop, as shown in Figure 9.

For the dc-bus voltage-control loop, it uses the dc bus capacitive energy  $E_{\text{Bus}}$  as state variable, and the supercapacitor delivered power  $p_{\text{SuperCREF}}$  as command variable, to obtain a natural linear transfer function for the system. If the losses in both the FC converter and supercapacitor converter are neglected, the dc link capacitive energy  $E_{\text{Bus}}$  is given versus supercapacitor

power  $p_{\text{SuperC}}$ , FC power  $p_{\text{FC}}$ , and load power  $p_{\text{Load}}$  by the following differential equation:

$$\frac{dE_{\text{Bus}}(t)}{dt} = p_{\text{SuperC}}(t) + p_{\text{FC}}(t) - p_{\text{Load}}(t). \quad (4)$$

The function  $F_1$  presented in Figure 9 is a voltage-to-energy transformation, proportional for the total dc-bus capacitance  $C_{\text{Bus}}$  to the square function

$$E_{\text{Bus}}(t) = \frac{1}{2} \cdot C_{\text{Bus}} \cdot v_{\text{Bus}}^2(t). \quad (5)$$

It enables the generation of both dc-bus energy reference  $E_{\text{BusREF}}$  and dc-bus energy measurement  $E_{\text{BusMea}}$ , through dc-bus voltage reference  $V_{\text{BusREF}}$  and dc-bus voltage measurement  $v_{\text{Bus}}$ , respectively. The dc-bus energy controller generates a supercapacitor power reference  $p_{\text{SuperCREF}}$ . This signal is then divided by the measured supercapacitor voltage  $v_{\text{SuperCMea}}$  and limited to maintain supercapacitor

voltage within an interval  $[V_{\text{SuperCMin}}, V_{\text{SuperCMax}}]$ . The higher value of this interval corresponds to the rated voltage of the storage device. Generally, the lower value  $V_{\text{SuperCMin}}$  is chosen as  $V_{\text{SuperCMax}}/2$ , resulting in the remaining energy in the supercapacitor bank of only 25%, which supercapacitor discharge becomes ineffective. This results in supercapacitor current reference  $i_{\text{SuperCREF}}$ .

The SuperC current-limitation function consists of limiting the reference  $i_{\text{SuperCREF}}$  to the interval  $[I_{\text{SuperCMin}}, I_{\text{SuperCMax}}]$  defined versus measured supercapacitor voltage  $v_{\text{SuperCMea}}$  as follows:

$$\left. \begin{aligned} I_{\text{SuperCMin}} &= -I_{\text{SuperCRated}} \\ &\cdot \min\left(1, \frac{V_{\text{SuperCMax}} - v_{\text{SuperCMea}}(t)}{\Delta V_{\text{SuperC}}}\right) \\ I_{\text{SuperCMax}} &= +I_{\text{SuperCRated}} \\ &\cdot \min\left(1, \frac{v_{\text{SuperCMea}}(t) - V_{\text{SuperCMin}}}{\Delta V_{\text{SuperC}}}\right) \end{aligned} \right\} \quad (6)$$

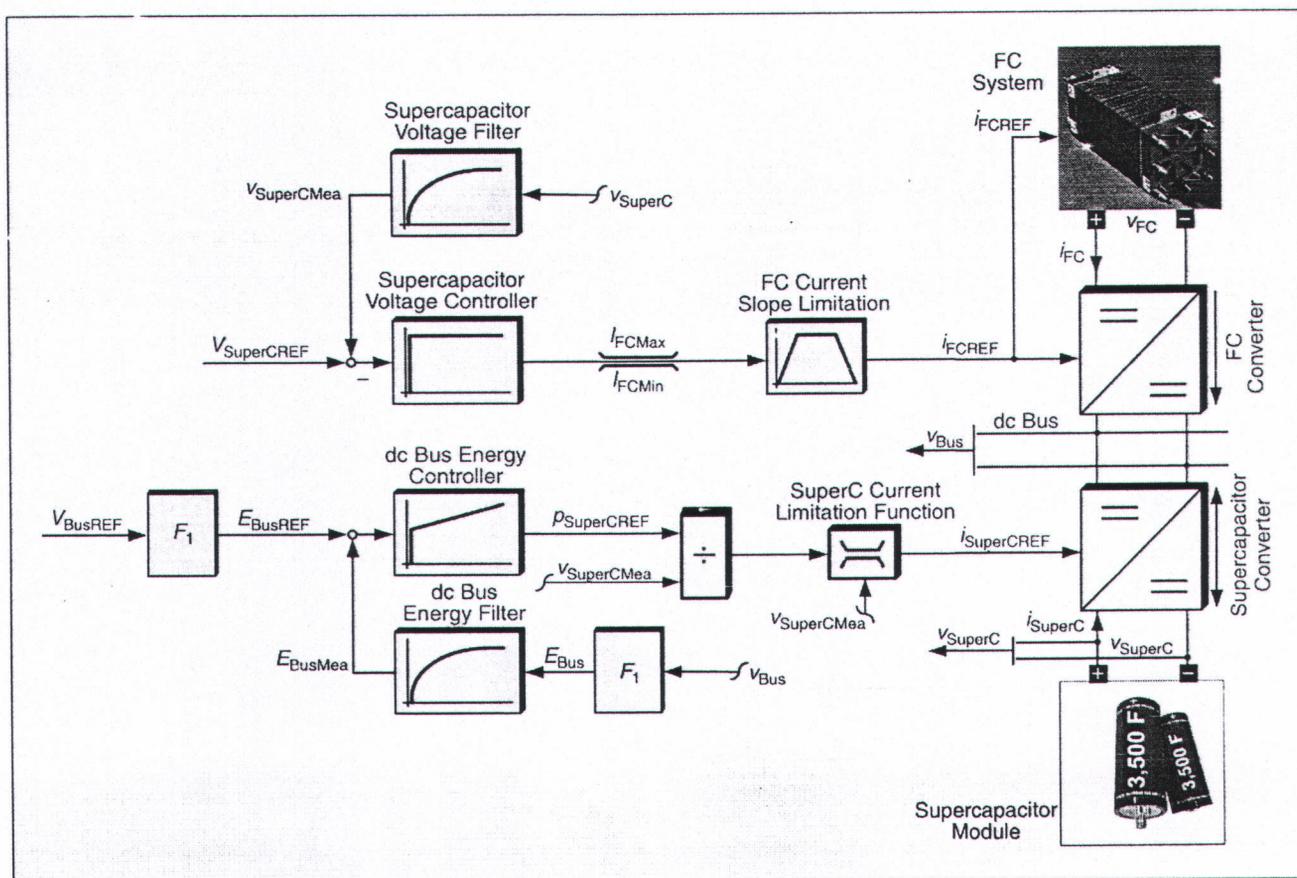


FIGURE 9—Proposed energy management of the FC/supercapacitor hybrid power source [25].

where  $I_{\text{SuperCRated}}$  and  $\Delta v_{\text{SuperC}}$  are regulation parameters.

For the supercapacitor voltage-regulation loop, the supercapacitor voltage controller generates an FC current reference  $i_{\text{FCREF}}$  limited in level and slope, with respect to constraints associated with the FC. The  $i_{\text{FCREF}}$  that drives the FC converter through the FC current loop is then kept within an interval  $[I_{\text{FCMin}}, I_{\text{FCRated}}]$ . The higher value of this interval corresponds to the rated current of the FC, and the lower value should be zero. Slope limitation to a maximum absolute value of some amperes per second enables safe operation of the FC, even during transient power demand.

Using this form of control principle, the state of the supercapacitor module is naturally defined through the dc-bus voltage regulation by the load power level and by its SOC. The following cases are encountered in narrow steady-state conditions.

- 1) If load power is negative, the dc link voltage regulation generates a negative supercapacitor current reference  $i_{\text{SuperCREF}}$ .
- 2) If load power is greater than the approximate FC-rated power, the dc-bus voltage regulation generates a positive supercapacitor current reference  $i_{\text{SuperCREF}}$ .
- 3) Otherwise, the state of the supercapacitor module depends on its SOC: for positive load power, supercapacitor current will therefore be positive if  $v_{\text{SuperC}} > v_{\text{SuperCREF}}$ , negative if  $v_{\text{SuperC}} < v_{\text{SuperCREF}}$ ; for negative load power, supercapacitor current will be always negative, even if  $v_{\text{SuperC}} > v_{\text{SuperCREF}}$  or  $v_{\text{SuperC}} < v_{\text{SuperCREF}}$ .

In all cases, the FC state depends only on supercapacitor voltage: FC current will be strictly positive and less than  $I_{\text{FCRated}}$ , if  $v_{\text{SuperC}} < v_{\text{SuperCREF}}$ ; otherwise, it will be zero. In transient conditions, as FC

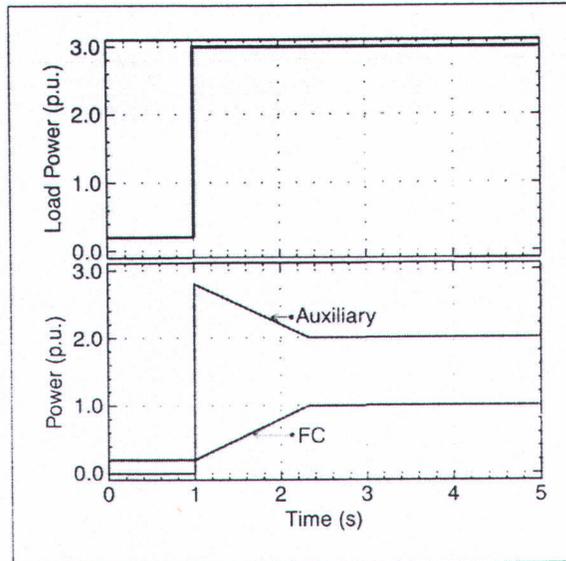


FIGURE 10—Simulation result: hybrid source response during a high-positive load step (power in p.u.).

current dynamics have been intentionally reduced, the supercapacitor supplies load variations. In effect, the dc-bus voltage regulation transforms a sudden increase in load power into a sudden increase of supercapacitor current and, on the contrary, a sudden decrease in load power into a sudden decrease of supercapacitor current.

### Conclusion of the Proposed Energy Management Algorithms

The important point in hybrid system presented here is to balance energy among the FC main source, auxiliary

source, and load. The FC power or current dynamics have been intentionally reduced; the auxiliary source supplies all load variations.

Finally, Figures 10 and 11 present simulation results during a high-constant stepped load power. They show the load, auxiliary, and FC powers in each unit. In simulations, the FC minimum and maximum powers are set at 0 p.u. (corresponding to the FC minimum current) and 1.0 p.u. (corresponding to the FC maximum current), respectively. The power dynamics of the FC is set at  $0.6 \text{ p.u.} \cdot \text{s}^{-1}$ . As illustrated in Figure 10, initially, the

storage device is full of charge, and the load power is 0.2 p.u. As a result, the power of the storage device is zero, and the FC supplies 0.2 p.u. for the constant load power. At  $t = 1 \text{ s}$ , the constant load power steps to 3.0 p.u. The following are the observations:

- the auxiliary source supplies most of the transient power required
- the FC power increases to the limited power 1.0 p.u. with a slope of  $0.6 \text{ p.u.} \cdot \text{s}^{-1}$
- synchronously, the auxiliary power, after a sharp increase (discharging), decreases slowly to a constant discharge of 2.0 p.u.

At steady state, the constant load power of 3.0 p.u. is entirely supplied by the FC of 1.0 p.u. and storage device of 2.0 p.u. (discharging state).

As a final simulation illustrated in Figure 11, initially, the auxiliary energy source is full of charge, and the load power is 0.8 p.u. As a result, the storage device power is zero, and the FC supplies 0.8 p.u. for the constant load power. At  $t = 1 \text{ s}$ , the constant load power steps to  $-1.0 \text{ p.u.}$  (imitated regenerative braking). The following are the observations:

- 1) the auxiliary source absorbs most of the transient negative power

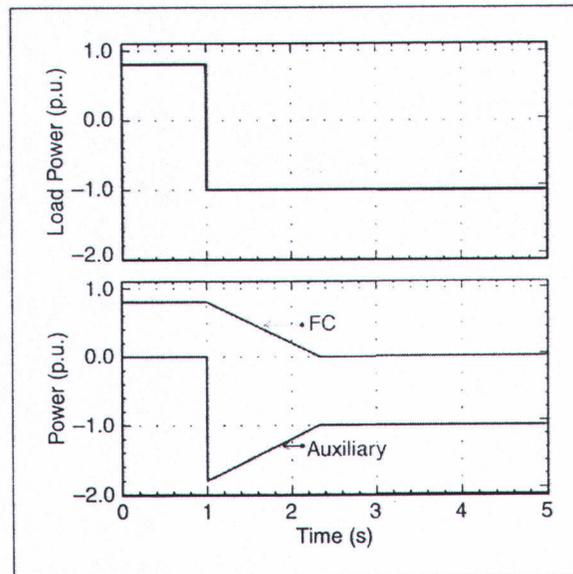


FIGURE 11—Simulation result: hybrid source response during a high-negative load step (imitated regenerative braking).

- 2) the FC power reduces to zero with a slope of  $0.6 \text{ p.u.} \cdot \text{s}^{-1}$ , because the FC power source is a unidirectional power flow
- 3) simultaneously, the auxiliary source, after a sharp decrease (charging), increases slowly to a constant charge at  $-1.0 \text{ p.u.}$

### Design Example for Hybrid Power Source

We design a full FC hybrid vehicle to present how to scale a power source and storage device with respect to applications. The vehicle specifications are as follows:

- average vehicle power = 40 kW
- storage device for the worse-case cycle during vehicle acceleration = 298 Wh
- dc-bus voltage for traction motors = 400 V.

Normally, we consider an FC size of the average vehicle power of 40 kW. In high-power applications, an interleaved multiphase boost converter is always selected as an FC converter [17]. Because the dc-bus voltage is equal to 400 V, the rated FC voltage is approximately equal to 200 V to operate a boost converter at 50% duty cycle for efficient switching utilization. For an FC/battery hybrid source, an FC is connected to the dc bus by a unidirectional dc/dc converter, and a battery bank is connected directly to the dc bus (Figure 8). The battery considered here is based on A123 systems' new high-power lithium ion ANR26650MI cell (2.3 Ah and 3.3 V). Each cell has a mass of 70 g. After adding 53 g for cell balancing and packaging, the total mass is 0.123 kg/cell. The published cost for six cells is US\$115 (including cell balancing and packaging). The upper current limit is 70 A. Because the dc-bus voltage is 400 V, 23 packs are used in a series so that the maximum battery voltage  $V_{\text{BatMax}}$  is 455 V. One defines 20% DOD from the battery. Then, to store the usable energy of 298 Wh, the two strings are needed to be connected in parallel. In this case,

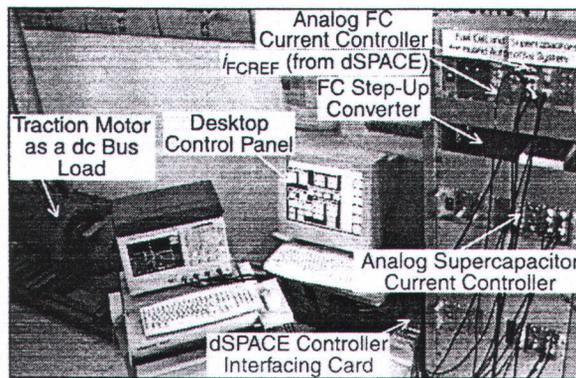


FIGURE 12 – Hybrid source test bench.

the required battery bank is as follows:

- pack in series: 23 packs
- string in parallel: two strings
- maximum battery voltage  $V_{\text{BatMax}}$ : 455 V
- nominal battery voltage  $V_{\text{BatNom}}$ : 400 V
- maximum energy content: 1,840 Wh =  $400 \text{ V} \times 2.3 \text{ Ah} \times 2$
- DOD: 20%
- usable energy: 368 Wh = 20% of maximum energy content
- peak power: 56 kW =  $70 \text{ A} \times 2 \times 400 \text{ V}$
- weight: 34 kg =  $0.123 \text{ kg} \times 6 \times 23 \times 2$
- cost: US\$5,290 = US\$115  $\times 23 \times 2$ .

For an FC/supercapacitor hybrid source, an FC is connected to the dc bus by a unidirectional dc/dc converter, and a supercapacitor bank is connected to the dc bus by a bidirectional dc/dc converter (Figure 9). The supercapacitor presented here is based on Maxwell Supercapacitor's BMOD0058 15-V pack, which contains six BCAP0350 cells (2.5 V, 350 F, and 95 A) in a series. The pack includes cell balancing and sturdy packaging. Because the dc-bus voltage is 400 V, the maximum supercapacitor pack voltage should be around 200 V (50% of

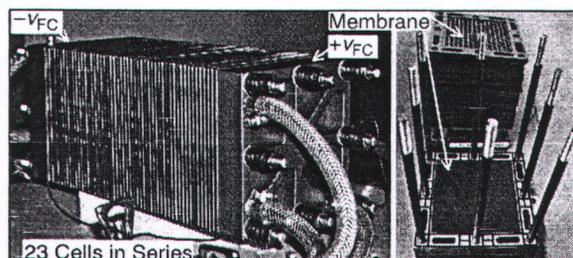


FIGURE 13 – PEMFC stack: 500 W, 40 A, and 13 V.

the dc-bus voltage), to operate a two-quadrant converter at a duty cycle of 50% (efficient switching utilization). Accordingly, 14 packs are used in a series so that the maximum supercapacitor voltage  $V_{\text{SuperCMax}}$  is 210 V. As a result, the nominal supercapacitor voltage  $V_{\text{SuperCNom}}$  is 200 V, and the minimum supercapacitor voltage  $V_{\text{SuperCMin}}$  is 100 V. To store the usable energy of 298 Wh, the 18 strings are needed to be connected in parallel. Based on correspondence with a Maxwell representative, a cost of US\$85 per 15-V pack is used for high-volume production. The mass of each pack is 680 g (including cell balancing and packaging). In this case, the required supercapacitor bank is as follows:

Based on correspondence with a Maxwell representative, a cost of US\$85 per 15-V pack is used for high-volume production. The mass of each pack is 680 g (including cell balancing and packaging). In this case, the required supercapacitor bank is as follows:

- pack in series: 14 packs
- string in parallel: 18 strings
- total capacitance,  $C$ :  $75 \text{ F} = ((350 \text{ F}/6)/14) \times 18$
- maximum supercapacitor voltage  $V_{\text{SuperCMax}}$ : 210 V
- nominal supercapacitor voltage  $V_{\text{SuperCNom}}$ : 200 V
- minimum supercapacitor voltage  $V_{\text{SuperCMin}}$ : 100 V
- usable energy: 313 Wh =  $(0.5 \cdot C \cdot V_{\text{SuperCNom}}^2 - 0.5 \cdot C \cdot V_{\text{SuperCMin}}^2) / 3,600$
- maximum energy content: 459 Wh =  $(0.5 \cdot C \cdot V_{\text{SuperCMax}}^2) / 3,600$
- peak power: 342 kW =  $95 \text{ A} \times 18 \times 200 \text{ V}$
- weight: 171 kg =  $0.68 \text{ kg} \times 14 \times 18$
- cost: US\$21,420 = US\$85  $\times 14 \times 18$ .

From the aforementioned estimations, it is very clear that an FC/supercapacitor vehicle must have at least 18 strings of supercapacitors in parallel to provide the amount of extra energy (298 Wh) required for acceleration.

This large number of supercapacitors increases the cost and mass of the vehicle.

### Experimental Validation

#### Test-Bench Description

A small-scale test bench of the hybrid systems in our laboratory is presented in Figure 12. As

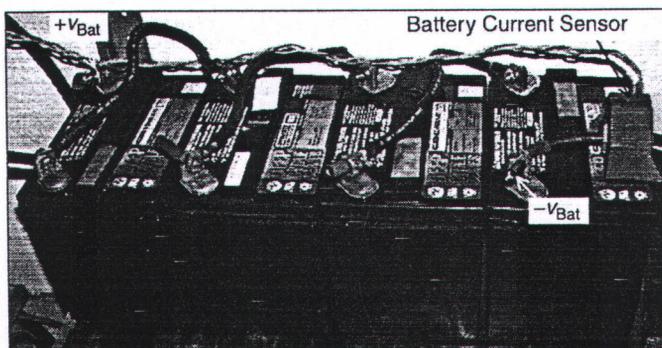


FIGURE 14—Lead-acid battery module: 33 Ah and 48 V.

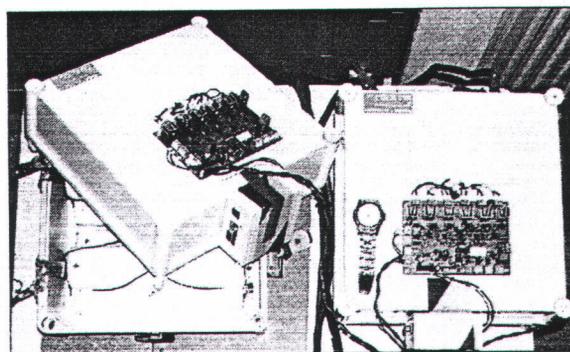


FIGURE 15—Supercapacitor module: 292 F, 30 V, and 500 A.

illustrated in Figure 13, the PEMFC system (500 W, 40 A, and 13 V) was achieved by ZSW, Germany. It is composed of 23 cells of 100 cm<sup>2</sup> in a series. It is supplied using pure hydrogen from bottles under pressure and with clean

and dry air from a compressor. The battery module (Figure 14) is obtained by means of four aged lead-acid batteries [7.78 Ah (33 Ah at name plate) and 12 V] connected in a series. The supercapacitor module (Figure 15) is obtained

by means of 12 SAFT supercapacitors SC3,500 (3,500 F, 2.5 V, 500 A, and a low-frequency ESR of 0.8 mΩ) connected in a series.

The load at dc bus is only a dc-traction motor drive (10 kW) coupled with a small-inertia flywheel. For the supercapacitor and FC current-control loops, they have been realized by analog circuits to function at high bandwidth. The proposed energy-control algorithms have been implemented in the real-time card dSPACE DS1104, through the mathematical environment of MATLAB-Simulink, with a sampling frequency of 25 kHz. The ControlDesk software enables changes in the parameters of the control loops.

The controlled parameters of the PEMFC are set as follows:

- 1)  $I_{FCMax} = 40$  A (rated FC current  $I_{FCRated}$ , corresponding to the rated FC power)
- 2)  $I_{FCMin} = 0$  A (minimum FC current, corresponding to the minimum FC power)
- 3) the FC current absolute slope limitation is set to  $4 \text{ A} \cdot \text{s}^{-1}$  (corresponding to the FC power slope of around  $50 \text{ W} \cdot \text{s}^{-1}$ ). This value has been experimentally determined as the highest current slope of our FC system, where no fuel starvation occurs [25].

### Performance of FC/Battery Hybrid Power Source

The controlled parameters of this system are set as follows:

- $SOC_{REF} = 100\%$  (equal to 7.78 Ah)
- $I_{BatMin} = -50$  A
- $I_{BatMax} = +6$  A
- $V_{BusMax} = 61$  V
- $\Delta v_{Bus} = 2$  V.

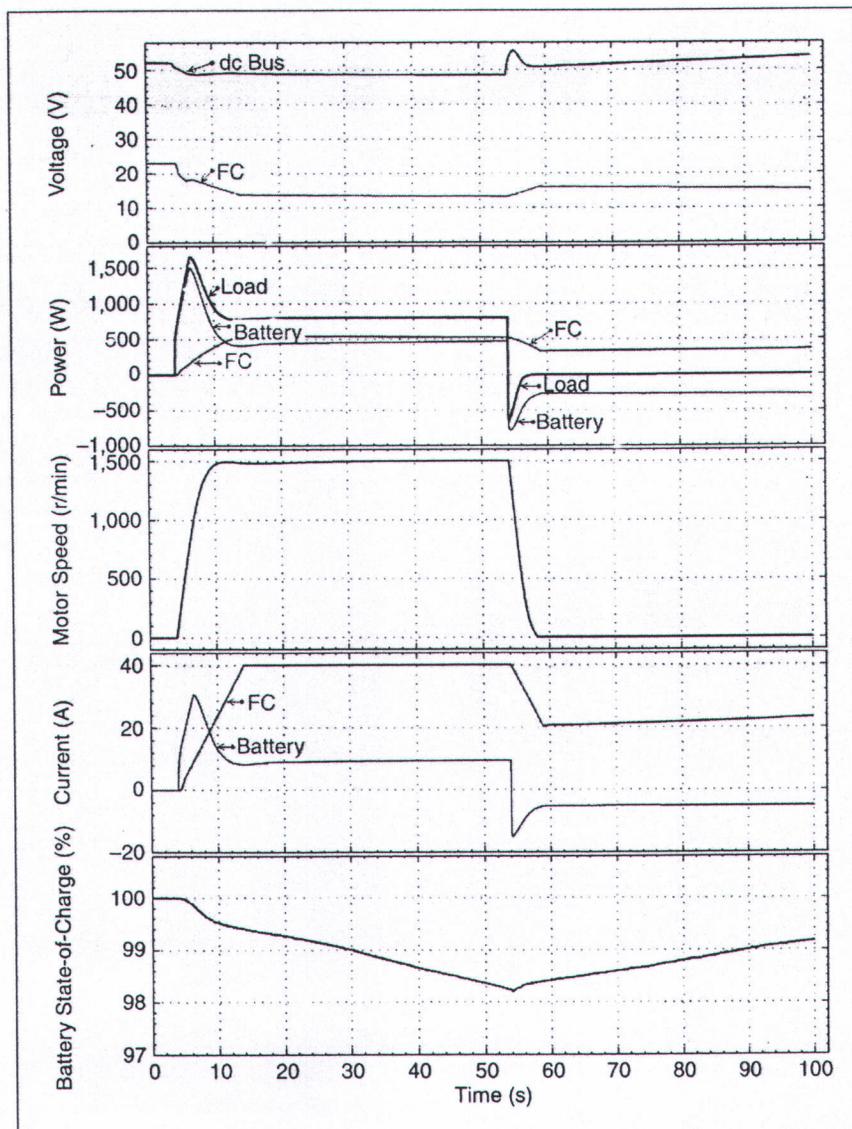


FIGURE 16—FC/battery hybrid source response during a motor-drive cycle.



Figure 16 presents waveforms obtained during the motor-drive cycle. It shows the dc-bus voltage (battery voltage), FC voltage, load power, battery power, FC power, motor speed, battery current, FC current, and battery SOC.

The initial state is zero for both the FC and battery powers and 100% for the battery SOC. At  $t = 4$  s, the motor starts to the final speed of 1,500 r/min, such that the final FC current is  $I_{FCRated}$ . The following can be observed:

- the battery supplies most of the power of 1,600 W required during motor acceleration
- the FC power increases with a limited slope up to a level of the rated power 500 W
- concurrently, the battery power, after a sharp increase during motor acceleration, decreases slowly to a constant discharging power of 400 W
- the steady-state load power at the constant speed of 1,500 r/min is about 800 W, entirely supplied by the FC and battery.

After that, at  $t = 54$  s, the motor reduces speed to stop. It can be scrutinized that there are three phases. First, the battery recovers the power supplied to the dc link by the FC and motor (known as a regenerative braking energy). Second, the battery recovers the reduced power supplied to the dc bus only by the FC. Third, the battery is charged at a constant current of  $-6$  A by the FC. During the first and second phases, the FC power reduces from a rated power of 500 W with a constant slope of  $50 \text{ W} \cdot \text{s}^{-1}$ . In the third phase, the FC power is nearly constant at around 300 W to charge the battery. After that, both the FC and battery power will reduce to zero when the SOC will reach  $\text{SOC}_{REF}$ . So, this characteristic can be comparable with the simulation results in Figures 10 and 11.

It must be noted here that the drive cycle in Figure 3 is not identical with that in Figure 16, because, in the test bench, the FC and storage devices are small-scale sizes. So, during

motor acceleration, there is no motor power limitation in Figure 16. In addition, during motor braking, the small regenerative braking energy is absorbed by the storage device, but in Figure 3 (real vehicle), the high regenerative braking energy is absorbed by the storage device; however, extra energy needs to be dissipated by a resistive braking during  $t = 48\text{--}51$  s in Figure 3.

### Performance of FC/ Supercapacitor Hybrid Power Source

The controlled parameters of this system are set as follows:

- $V_{\text{BusREF}} = 42 \text{ V}$  (a new standard dc-bus voltage in an automotive

electrical system called Power-Net [11])

- $V_{\text{SuperCREf}} = 25 \text{ V}$
- $V_{\text{SuperCMax}} = 30 \text{ V}$
- $V_{\text{SuperCMin}} = 15 \text{ V}$
- $I_{\text{SuperCRated}} = 200 \text{ A}$
- $\Delta V_{\text{SuperC}} = 0.5 \text{ V}$ .

Figure 17 presents waveforms obtained during the motor-drive cycle. It shows the dc-bus voltage, FC voltage, load power, supercapacitor power, FC power, motor speed, supercapacitor current, FC current, and supercapacitor voltage (or supercapacitor SOC).

The initial state is no-load power, and the storage device full of charge,  $V_{\text{SuperC}} = 25 \text{ V}$ ; as a result, zero for both the FC and supercapacitor

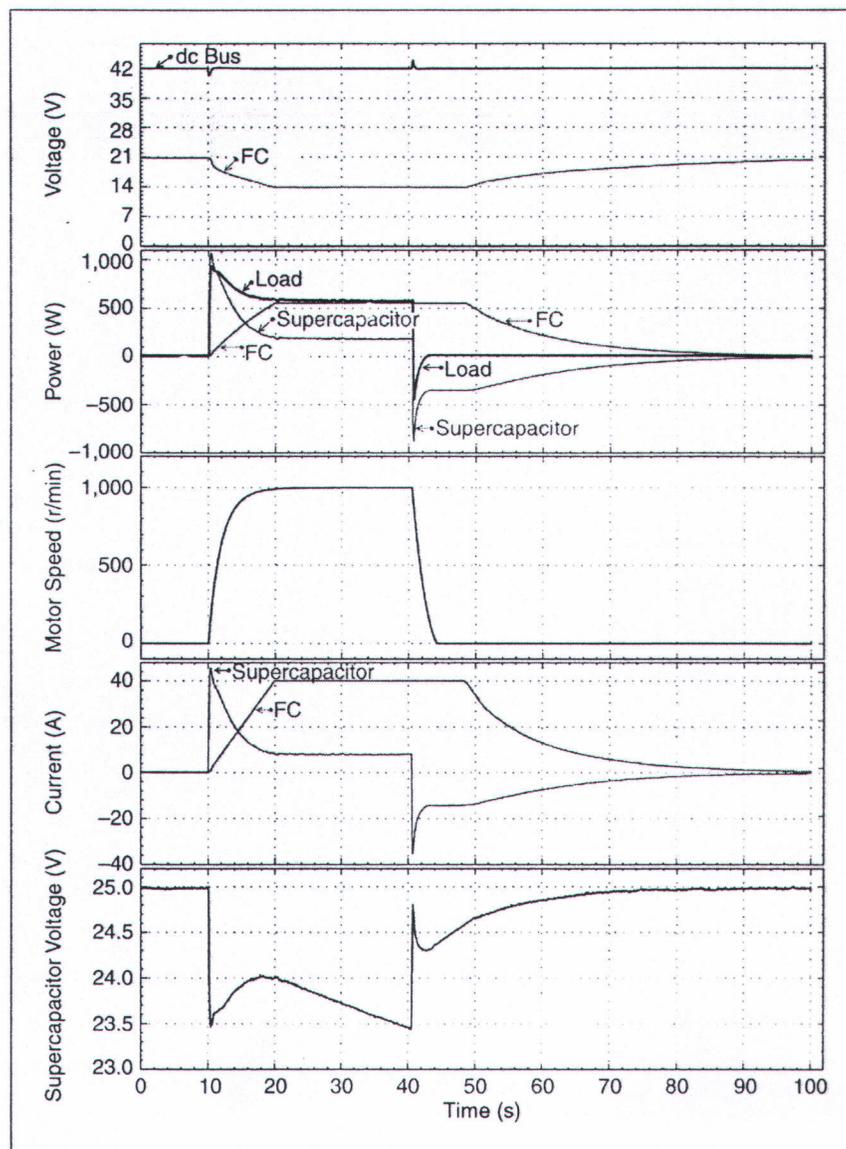


FIGURE 17 – FC/supercapacitor hybrid source response during a motor-drive cycle.

powers. At  $t = 10$  s, the motor speed accelerates to the final speed of 1,000 r/min; synchronously, the final FC power increases with a limited slope of  $50 \text{ W} \cdot \text{s}^{-1}$  to a rated power of 500 W. Therefore, the supercapacitor, which supplies most of the power required during motor acceleration, remains in a discharge state after the motor start, because the steady-state load power (approximately 600 W) is greater than the FC-rated power (500 W), and the peak load power is about 1,000 W, which is about two times that of the FC-rated power.

After that, at  $t = 40$  s, the motor speed decelerates to stop with a peak load power of about  $-500$  W. The supercapacitor is deeply charged, demonstrating the three phases. First, the supercapacitor recovers the energy supplied to the dc bus by the FC (500 W) and the traction motor. Second, the supercapacitor is charged only by the FC. Third, the supercapacitor is nearly full of charge, then reducing the charging current. After that, both the FC and supercapacitor powers reduce to zero when  $V_{\text{SuperC}}$  reaches  $V_{\text{SuperCREF}}$  of 25 V. Excellently, only small perturbations on the dc-bus voltage waveform can be seen, which is of major importance in using supercapacitors to improve the dynamic performance of the whole system. These characteristics can be again comparable with the simulation results in Figures 10 and 11.

## Conclusions

An FC vehicle can benefit from being hybridized with an energy storage device (battery or supercapacitor). The advantages could include improved vehicle performance and fuel economy and lower system cost. The degree of hybridization benefits from FC efficiency characteristics, FC downsizing, displacing FC tasks with the secondary source functionality, or energy recovery through regenerative braking. The role of batteries and supercapacitors in FC hybrid vehicles is studied to understand their potential impact on dynamic performances.

Energy storage devices can advance the load, following the

characteristics of a main source by providing a stronger power response to changes in system loading. During motor starts/stops or other considerable steps in load, the energy storage devices provide the balance of energy needed during the temporary load-transition periods and also absorb excess energy from the generator source (motor braking). Adding energy storage to distributed power systems improves power quality and efficiency and reduces capital expenses by allowing the systems to be sized more closely to the steady-state power requirements, rather than oversizing the main generator to meet transient loading requirements.

Experimental results with a small-scale hybrid test bench in the laboratory have evidently shown the possibility of improving the performance of the whole system and validated the proposed control algorithms: FC/battery hybrid source and FC/supercapacitor hybrid source.

In general, an FC/supercapacitor hybrid has better performance, because a supercapacitor can more effectively assist an FC to meet transient power demand (supercapacitors can be charged or discharged at high current, where a battery cannot function), and high-current charges and discharges from batteries will also have a reduced lifetime.

Nevertheless, an FC hybrid vehicle with supercapacitors as the only energy storage will have deficiency or even malfunction during the vehicle start up, because the start up time of a PEMFC is around 5–10 min, where the battery has higher specific energy than supercapacitor.

Subsequently, a more practical solution will be an FC/battery/supercapacitor hybrid power source. So, the future studies may be a hybrid source of FC/battery/supercapacitor combination. A main advantage of the FC/battery/supercapacitor vehicle is the increase in the battery lifetime due to reduction of high-current charges and discharges.

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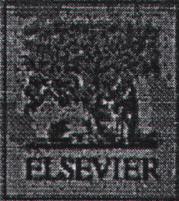
## References

- [1] A. R. Miller, K. S. Hess, D. L. Barnes, and T. L. Erickson, "System design of a large fuel cell hybrid locomotive," *J. Power Sources*, vol. 173, pp. 935–942, Nov. 2007.

- [2] S. Pasricha, M. Keppler, S. R. Shaw, and M. H. Nehrir, "Comparison and identification of static electrical terminal fuel cell models," *IEEE Trans. Energy Convers.*, vol. 22, pp. 746-754, Sept. 2007.
- [3] P. Corbo, F. E. Corcione, F. Migliardini, and O. Veneri, "Experimental assessment of energy-management strategies in fuel-cell propulsion systems," *J. Power Sources*, vol. 157, no. 2, pp. 799-808, July 2006.
- [4] P. Thounthong, S. Raël, and B. Davat, "Test of a PEM fuel cell with low voltage static converter," *J. Power Sources*, vol. 153, pp. 145-150, Jan. 2006.
- [5] T. Montani, "Electric energy storage evaluation for urban rail vehicles," in *Proc. European Conf. Power Electronics and Applications (EPE'03)*, Toulouse, France, Oct. 2003, pp. 1-10.
- [6] T. Furuya, K. Kondo, and T. Yamamoto, "Experimental study on a PEMFC fed railway vehicle motor drive system," in *Proc. 41st IEEEIAS*, Oct. 8-12, 2006, pp. 1249-1252.
- [7] T. Yoneyama, T. Yamamoto, K. Kondo, T. Furuya, and K. Ogawa, "Fuel cell powered railway vehicle and experimental test results," in *Proc. European Conf. Power Electronics and Applications (EPE'07)*, Sept. 2-5, 2007, pp. 1-10.
- [8] T. Ogawa, H. Yoshihara, S. Wakao, K. Kondo, and M. Kondo, "Energy consumption analysis of FC-EDLC hybrid railway vehicle by dynamic programming," in *Proc. European Conf. Power Electronics and Applications (EPE'07)*, Sept. 2-5, 2007, pp. 1-10.
- [9] M. C. Péra, D. Candusso, D. Hissel, and J. M. Kauffmann, "Power generation by fuel cells," *IEEE Ind. Electron. Mag.*, vol. 1, no. 3, pp. 28-37, 2007.
- [10] M. Tekin, D. Hissel, M. C. Péra, and J. M. Kauffmann, "Energy-management strategy for embedded fuel-cell systems using fuzzy logic," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 595-603, Feb. 2007.
- [11] P. Thounthong, B. Davat, and S. Raël, "Drive friendly," *IEEE Power Energy Mag.*, vol. 6, no. 1, pp. 69-76, 2008.
- [12] S. Jemei, D. Hissel, M. C. Péra, and J. M. Kauffmann, "A new modeling approach of embedded fuel-cell power generators based on artificial neural network," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 437-447, Jan. 2008.
- [13] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237-2245, June 2008.
- [14] J. M. Corrêa, F. A. Farret, L. N. Canha, and M. G. Simões, "An electrochemical-based fuel-cell model suitable for electrical engineering automation approach," *IEEE Trans. Ind. Electron.*, vol. 51, pp. 1103-1112, Oct. 2004.
- [15] J. M. Corrêa, F. A. Farret, V. A. Popov, and M. G. Simões, "Sensitivity analysis of the modeling used in simulation of proton exchange membrane fuel cells," *IEEE Trans. Energy Convers.*, vol. 20, pp. 211-218, Jan./Mar. 2005.
- [16] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle," *J. Power Sources*, vol. 158, pp. 806-814, July 2006.
- [17] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel cell high-power applications," *IEEE Ind. Electron. Mag.*, vol. 3, no. 1, pp. 32-46, Mar. 2009.
- [18] T. Zhu, S. R. Shaw, and S. B. Leeb, "Transient recognition control for hybrid fuel cell systems," *IEEE Trans. Energy Convers.*, vol. 21, pp. 195-201, Mar. 2006.
- [19] C. Wang and M. H. Nehrir, "Load transient mitigation for standalone fuel cell power generation systems," *IEEE Trans. Energy Convers.*, vol. 22, no. 4, pp. 864-872, Dec. 2007.
- [20] R. Gaynor, F. Mueller, F. Jabbari, and J. Brouwer, "On control concepts to prevent fuel starvation in solid oxide fuel cells," *J. Power Sources*, vol. 180, no. 1, pp. 330-342, May 2008.
- [21] W. Schmittinger and A. Vahidi, "A review of the main parameters influencing long-term performance and durability of PEM fuel cells," *J. Power Sources*, vol. 180, pp. 1-14, May 2008.
- [22] J. Wu, X. Z. Yuan, J. J. Martin, H. Wang, J. Zhang, J. Shen, S. Wu, and W. Merida, "A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies," *J. Power Sources*, vol. 184, no. 1, pp. 104-119, Sept. 2008.
- [23] N. Yousfi-Steiner, Ph. Moçotéguy, D. Candusso, D. Hissel, A. Hernandez, and A. Aslanides, "A review on PEM voltage degradation associated with water management: Impacts, influent factors and characterization," *J. Power Sources*, vol. 183, no. 1, pp. 260-274, Aug. 2008.
- [24] A. Taniguchi, T. Akita, K. Yasuda, and Y. Miyazaki, "Analysis of electrocatalyst degradation in PEMFC caused by cell reversal during fuel starvation," *J. Power Sources*, vol. 130, pp. 42-49, May 2004.
- [25] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell and supercapacitors association for distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 3225-3233, Dec. 2007.
- [26] P. Corbo, F. Migliardini, and O. Veneri, "An experimental study of a PEM fuel cell power train for urban bus application," *J. Power Sources*, vol. 181, no. 2, pp. 363-370, July 2008.
- [27] A. Khaligh and A. Emadi, "Mixed DCM/CCM pulse adjustment with constant power loads," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 44, no. 2, pp. 766-782, Apr. 2008.
- [28] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, pp. 2258-2267, June 2008.
- [29] J. Bauman and M. Kazerani, "A comparative study of fuel-cell-battery, fuel-cell-ultracapacitor, and fuel-cell-battery-ultracapacitor," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 760-769, Mar. 2008.
- [30] M. Ceraolo, A. di Donato, and G. Franceschi, "A general approach to energy optimization of hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1433-1441, May 2008.
- [31] Y. S. Lee, W. Y. Wang, and T. Y. Kuo, "Soft computing for battery state-of-charge (BSOC) estimation in battery string systems," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 229-239, Jan. 2008.
- [32] A. Szumanowski and Y. Chang, "Battery management system based on battery nonlinear dynamics modeling," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1425-1432, May 2008.
- [33] M. Coleman, C. K. Lee, C. Zhu, and W. G. Hurley, "State-of-charge determination from EMF voltage estimation: using impedance, terminal voltage, and current for lead-acid and lithium-ion batteries," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2550-2557, Oct. 2007.
- [34] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of dc/dc converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721-2735, Sept. 2008.
- [35] S. Lu, K. A. Corzine, and M. Ferdowsi, "A new battery/ultracapacitor energy storage system design and its motor drive integration for hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1516-1523, July 2007.
- [36] Y. P. Yang, J. J. Liu, T. J. Wang, K. C. Kuo, and P. E. Hsu, "An electric gearshift with ultracapacitors for the power train of an electric vehicle with a directly driven wheel motor," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2421-2431, Sept. 2007.
- [37] J. Wang, B. Taylor, Z. Sun, and D. Howe, "Experimental characterization of a supercapacitor-based electrical torque-boost system for downsized ICE vehicles," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3674-3681, Nov. 2007.
- [38] M. Uzunoglu and M. S. Alam, "Modeling and analysis of an FC/UC hybrid vehicular power system using a novel-wavelet-based load sharing algorithm," *IEEE Trans. Energy Convers.*, vol. 23, pp. 263-272, Mar. 2008.
- [39] M. Ortúzar, J. Moreno, and J. Dixon, "Ultra-capacitor-based auxiliary energy system for an electric vehicle: implementation and evaluation," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2147-2156, Aug. 2007.
- [40] I. Sadli, P. Thounthong, J. P. Martin, S. Raël, and B. Davat, "Behaviour of a PEMFC supplying a low voltage static converter," *J. Power Sources*, vol. 156, pp. 119-125, May 2006.
- [41] M. H. Todorovic, L. Palma, and P. N. Enjeti, "Design of a wide input range dc-dc converter with a robust power control scheme suitable for fuel cell power conversion," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 2247-2255, Mar. 2008.
- [42] R. J. Wai, C. Y. Lin, R. Y. Duan, and Y. R. Chang, "High-efficiency dc-dc converter with high voltage gain and reduced switch stress," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 354-364, Feb. 2007.
- [43] R. S. Gemmen, M. C. Williams, and K. Gerdes, "Degradation measurement and analysis for cells and stacks," *J. Power Sources*, vol. 184, no. 1, pp. 251-259, Sept. 2008.
- [44] Z. Jiang, L. Gao, and R. A. Dougal, "Adaptive control strategy for active power sharing in hybrid fuel cell/battery power sources," *IEEE Trans. Energy Convers.*, vol. 22, pp. 507-515, June 2007.
- [45] P. Fontela, A. Soria, J. Mielgo, J. F. Sierra, J. de Blas, L. Gauchia, and J. M. Martinez, "Airport electric vehicle powered by fuel cell," *J. Power Sources*, vol. 169, no. 1, pp. 184-193, June 2007.
- [46] M. B. Camara, D. Fodorean, D. Bouquain, H. Gualous, and A. Miraoui, "Hybrid sources control for electric drives traction applications," in *Proc. IEEE Int. Symp. Power Electronics, Electrical Drives, Automation and Motion*, June 11-13, 2008, pp. 744-749.
- [47] A. Khaligh, "Realization of parasitics in stability of DC-DC converters loaded by constant power loads in advanced multi-converter automotive systems," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2295-2304, June 2008.
- [48] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel starvation: Analysis of a PEM fuel cell," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 52-59, July/Aug. 2009.
- [49] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Convers.*, vol. 23, pp. 148-155, Mar. 2008.
- [50] A. Payman, S. Pierfederici, and F. Meibody-Tabar, "Energy control of supercapacitor/fuel cell hybrid power source," *Energy Convers. Manage.*, vol. 49, no. 6, pp. 1637-1644, June 2008.
- [51] P. Thounthong, S. Raël, and B. Davat, "Analysis of supercapacitor as second source based on fuel cell power generation," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 247-255, Mar. 2009.

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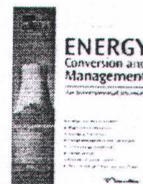
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## Study of a multiphase interleaved step-up converter for fuel cell high power applications

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## ABSTRACT

This paper presents a study of a high power dc distributed system supplied by a fuel cell generator. A proposed parallel power converter with interleaving algorithm is chosen to boost a low dc voltage of fuel cell to a dc bus utility level. The present interleaved step-up converters are composed of two and four identical boost converters connected in parallel. Converters are controlled by interleaved switching signals, which have the same switching frequency and the same phase shift. By virtue of paralleling the converters, the input current can be shared among the cells or phases, so that high reliability and efficiency in power electronic systems can be obtained. In addition, it is possible to improve the system characteristics such as maintenance, repair, fault tolerance, and low heat dissipation. During the past decade, power electronics research has focused on the development of interleaved parallel converters. For an interleaving technique with a real fuel cell source, this work is the first presentation; it is not just a fuel cell simulation. So, the design and experimental verification of 1.2-kW prototype converters at a switching frequency of 25 kHz connected with a Nexa™ PEM fuel cell system (1.2-kW, 46-A) in a laboratory is presented. Experimental results corroborate the excellent system performances. The fuel cell ripple current can be virtually reduced to zero. As a result, the fuel cell mean current is nearly equal to the fuel cell rms current.

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## 1. Introduction

Fuel cell (FC) technology is nowadays considered as a promising alternative for growing energy request and cleaner environment. The power and energy efficiency of FC is highly dependent on the thermodynamics, electrode kinetics, reactant mass transfer, as well as materials and components for assembling the FC stack. These factors have been addressed throughout the FC history, and are now still the major challenges for FC research and development [1].

There are several types of FCs, which are characterized by the electrolyte used. One of the most promising is the small, lightweight and relatively easy to build polymer electrolyte membrane FC (PEMFC) [2]. To make the FC stack be operable, one has to supply fuel, air and water to the stack; and remove the water product from the stack; as well as optimize the temperature and humidity. Therefore, many complex components have to be integrated together in a FC system including air blower, fuel pump, sensors, heat

exchanger, fuel reservoir, fuel mixer, startup batteries and electronic controller [3].

Thounthong et al. [4] experimented with a 500-W PEMFC system and Ahmed et al. [5] experimented with a 1200-W Nexa™ PEMFC system have demonstrated that the electrical response time of a FC is generally fast, being mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. On the other hand, because a FC system is composed of many mechanical devices, the whole FC system has slow transient response and slow output power ramping.

For clarity, Figs. 1 and 2 illustrate a PEMFC system (0.5-kW, 40-A) voltage response to a current demand. The tests operate in two different ways: current step (Fig. 1) and current slope (Fig. 2). One can scrutinize the voltage drop in Fig. 1, compared to Fig. 2, because fuel flows (particularly the delay of air flow) have difficulties following the current step. This characteristic is called "fuel starvation phenomenon" [4]. This condition of operation is evidently dangerous for the FC stack, as already demonstrated by Taniguchi et al. [6].

Thus, to utilize the FC in dynamic applications, a control system must limit its current slope as depicted in Fig. 3, refer to a block diagram "FC Current Slope Limitation", as detailed by Thounthong et al. [7]. As a result, the electrical system supplied by a FC must

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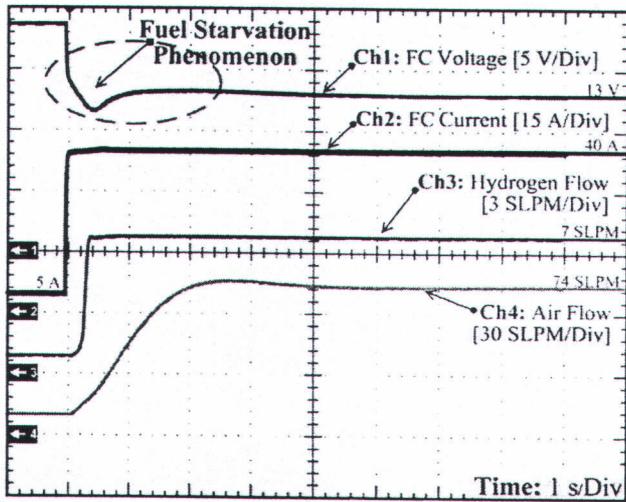


Fig. 1. Fuel cell dynamic characteristics to a high current step. It can be observed the phenomenon of fuel starvation due to a high inertia of mechanical devices in the fuel cell system. Note that SLPM stands for standard liter per minute.

have at least an auxiliary power source (battery [8] or supercapacitor [9]) to improve the system performances when electrical loads demand high energy in a short time (for example, vehicle acceleration and deceleration). It means that a FC power source is always operating with at least a supplementary source, called a hybrid source system as illustrated in Fig. 3.

FC produces low dc voltage, so that it is most often connected to electric power networks through a step-up (boost) converter (Fig. 3). The major problems of using a single dc/dc converter connected with FC in high power applications (for example: 50–100 kW in FC vehicle) are as follows:

- (1) difficulty of the design of magnetic component: ferrite core (a core used to build an inductor or an electric transformer; there are two kinds of core applications following the size and frequencies: for signal inductor or transformer and for power inductor or transformer) and Litz-wire size (Litz-wire is a type of cable used in power electronic applications. The wire is designed to reduce the skin effect and proximity

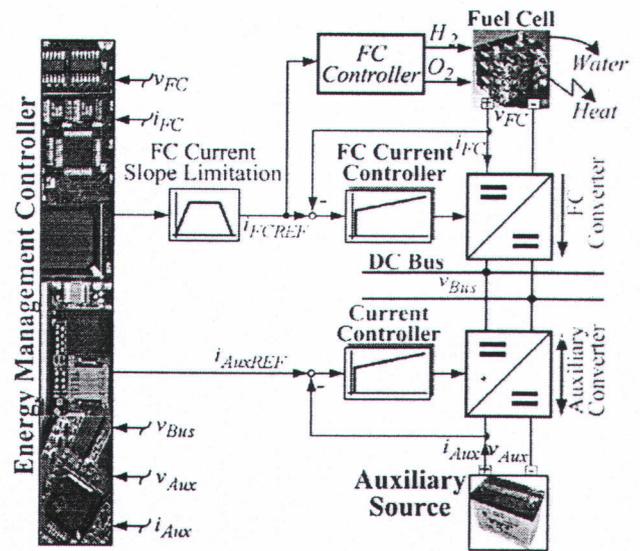
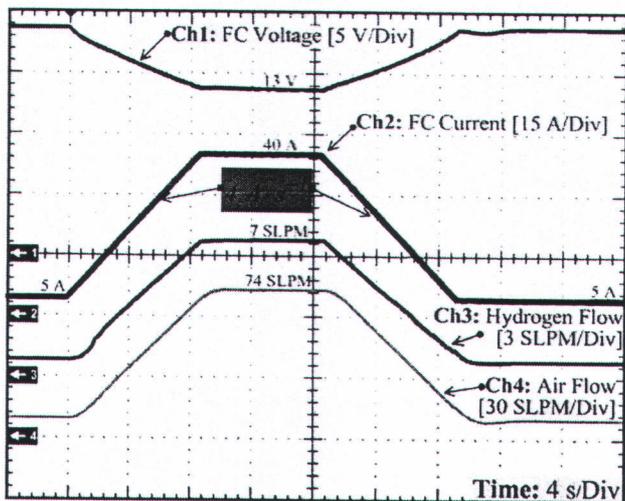


Fig. 3. Concept of hybrid power source: FC as a main source and a storage device (supercapacitor or battery) as an auxiliary source [8]. Each converter must be current controlled. For FC current, a current slope limitation (refer to “FC Current Slope Limitation”) must be added to circumvent the fuel starvation problem.

effect losses in conductors. It consists of many thin wires, individually coated with an insulating film and twisted or woven together, following one of several carefully prescribed patterns often involving several levels);

- (2) high FC ripple current, in which may lead to reduce its stack lifetime.

Therefore, by paralleling converters with interleaving technique, these problems can be avoided.

This paper presents the concept of parallel step-up converter with interleaving technique for a FC power source. It will provide a significant contribution to the field of the fuel cell power conditioning, particularly in fuel cell high power applications. The advantages of the proposed topology are as follows:

- (1) Size and volume of passive devices (inductor and capacitor) are reduced.
- (2) Ripple of the input and output waveforms are reduced.
- (3) Ripple frequency of the input and output waveforms are increased.
- (4) Power converter is modular. It enhances reliability of the system, and increases converter power rating by paralleling phases, not by paralleling multiple devices.
- (5) Thermal management is simple. The primary driver in all paralleling schemes for lower power applications is the decentralized heat dissipation of the parallel power converters.
- (6) Current ratings of power electronic components are reduced, because current ratings are proportional to the continuous power rating of the circuit.

Section 2 in the paper describes the multi-modules of power circuit connection, the proposed FC current control loop, and the dynamic system equations. The 1.2-kW FC converters of 2-phase and 4-phase parallel converters are built and tested with a Nexa™ PEM fuel cell system (1.2-kW, 46-A by Ballard Power Systems Inc.) in laboratory. To operate at a high bandwidth and a high switching

by means of analog circuits. Experimental results in Section 3 will illustrate the system performances.

**2. Multiphase interleaved boost converter for fuel cell power source**

**2.1. Power circuit**

In fuel cell higher power applications and higher dc voltage distribution, a step-up converter (or boost converter) is a necessity. Passive solutions were developed first, which required massive inductors and capacitors. The fuel cell boost converter sizes of 0.5 kW [8]; 1 kW [10]; 5 kW [11]; 27 kW [12]; and 50 kW [13] have been studied. However, a classical boost converter will be limited when the power increases or for higher step-up ratios. To reduce the volume of these huge solutions active switching with interleaving technique using a boost topology was developed. The active solutions had higher power densities than the passive solutions. Interleaving regulator is the next step in increasing regulator power densities, reducing the overall volume of the design. Interleaving will reduce magnetic volume and has the added benefit of reducing RMS current in the boost capacitor [14].

The active method of interleaving is nowadays well known [15]. In the interleaving method, the modules operate at the same switching frequency. Their switching waveforms are displaced in phase over a switching period with respect to one another by  $2\pi/N$  radians,  $N$  being the number of converters in parallel [16,17]. It is important to note here that, according to [4] a high FC current ripple plays an important role in its catalyst lifetime. Especially, sharp current rise/fall and large magnitude of current ripple should be avoided. Here, the proposed multiphase parallel boost converter for high power FC applications is depicted in Fig. 4.

**2.2. Current control loops of the parallel converter**

The proposed current control loops of the  $N$ -phase interleaved converter are depicted in Fig. 5. When a FC operates, its fuel (hydrogen and oxygen) flows are controlled by a “fuel cell controller”. The fuel flows must be adjusted to match the reactant delivery rate to the usage rate by the “FC controller”. For this reason, the in-

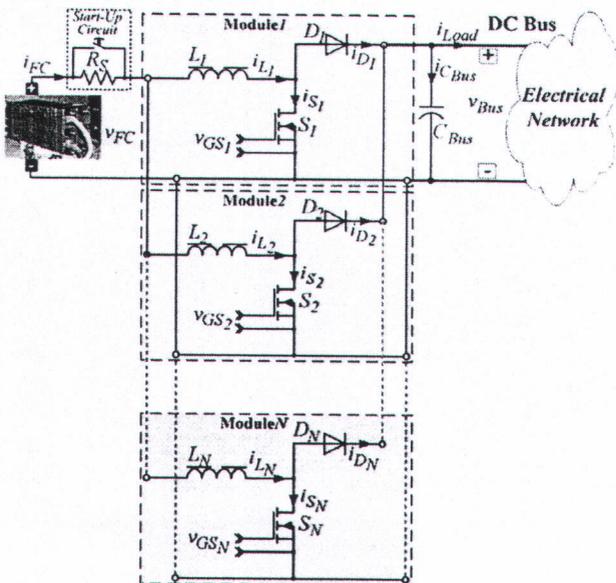


Fig. 4. Multiphase interleaved boost converter for FC power source.

ner FC current control loop is mandatory. So, the control algorithm (dc bus energy [7] or voltage control loop) demands energy from FC to dc link by generating  $i_{FCREF}$ . One can take advantage of the safety and high dynamic characteristics of this loop as well; thus, it may be realized by analog circuits to function at high bandwidth.

To obtain the transfer function of the FC current control loop, the linearized differential equations (which are developed from the switched state-space model through the state-space averaged model of a boost converter) are defined as follows [18,19]:

$$\begin{cases} L_1 \frac{d\tilde{i}_{L_1}(t)}{dt} &= \tilde{v}_{FC}(t) - R_{L_1}\tilde{i}_{L_1}(t) - (1 - D_1)\tilde{v}_{Bus}(t) + V_{Bus}\tilde{d}_1(t) \\ L_2 \frac{d\tilde{i}_{L_2}(t)}{dt} &= \tilde{v}_{FC}(t) - R_{L_2}\tilde{i}_{L_2}(t) - (1 - D_2)\tilde{v}_{Bus}(t) + V_{Bus}\tilde{d}_2(t) \\ \vdots & \vdots \\ L_N \frac{d\tilde{i}_{L_N}(t)}{dt} &= \tilde{v}_{FC}(t) - R_{L_N}\tilde{i}_{L_N}(t) - (1 - D_N)\tilde{v}_{Bus}(t) + V_{Bus}\tilde{d}_N(t) \\ C_{Bus} \frac{d\tilde{v}_{Bus}(t)}{dt} &= (1 - D_1)\tilde{i}_{L_1}(t) - I_{L_1}\tilde{d}_1(t) + (1 - D_2)\tilde{i}_{L_2}(t) - I_{L_2}\tilde{d}_2(t) \\ &+ (1 - D_N)\tilde{i}_{L_N}(t) - I_{L_N}\tilde{d}_N(t) - \tilde{i}_{Load}(t) \end{cases} \quad (1)$$

where the subscript numbers (1, 2, ..., N) represent parameters of each converter module, and  $D$  is the nominal duty cycle of the PWM converter;  $\tilde{d}$ , the duty cycle variation;  $V_{Bus}$ , the nominal dc bus voltage;  $\tilde{v}_{Bus}$ , the dc bus voltage variation;  $I_{L_i}$ , the nominal inductor current;  $\tilde{i}_{L_i}$ , the inductor current variation;  $\tilde{i}_{Load}$ , the load current variation and  $R_L$  is the series resistance of inductor  $L$ .

Note that series resistance of  $C_{Bus}$  is ignored.

As portrayed in Fig. 5, for current measurements of each inductor current, a first order filter  $H_{IN}(s)$  is used to reduce harmonics due to high switching frequency. A classical proportional–integral (PI) controller  $C_{IN}(s)$  associated to a pulse width modulation (PWM) generator  $G_{PN}(s)$  is selected for inductor current control. If we consider that the parameters in each converter are ideally the same values, the inductor current control loops can be modeled from (1), taking into account  $V_p$ , the amplitude of the PWM saw tooth carrier signals, by the following closed-loop transfer function:

$$\frac{\tilde{i}_L(s)}{\tilde{i}_{LREF}(s)} = \frac{C_i(s)G_p(s)G_{id}(s)}{1 + C_i(s)G_p(s)G_{id}(s)H_i(s)} \quad (2)$$

with

$$C_i(s) = \frac{K_i(T_{Ci}s + 1)}{T_{Ci}s} \quad (3)$$

$$G_p(s) = \frac{1}{V_p} \quad (4)$$

$$H_i(s) = \frac{K_f}{T_f s + 1} \quad (5)$$

$$G_{id}(s) = \frac{\tilde{i}_L(s)}{\tilde{d}} = \frac{K_{id}(T_z s + 1)}{\left(\frac{s}{\omega_n}\right)^2 + \frac{2\zeta}{\omega_n}s + 1} \quad (6)$$

and

$$\begin{cases} K_{id} = \frac{I_L}{(1-D)} \text{ and } \omega_n = \sqrt{\frac{(1-D)^2}{L C_{Bus}}} \\ T_z = \frac{V_{Bus} C_{Bus}}{(1-D)I_L} \text{ and } \zeta = \frac{R_L C_{Bus} \omega_n}{(1-D)^2} \end{cases} \quad (7)$$

The gain  $K_i$  and the integral time constant  $T_{Ci}$  of the PI controller are set to obtain the desired phase margin. For the equations above, we consider that the FC power source is an ideal source (no FC complex impedances [20,21] taken into account).

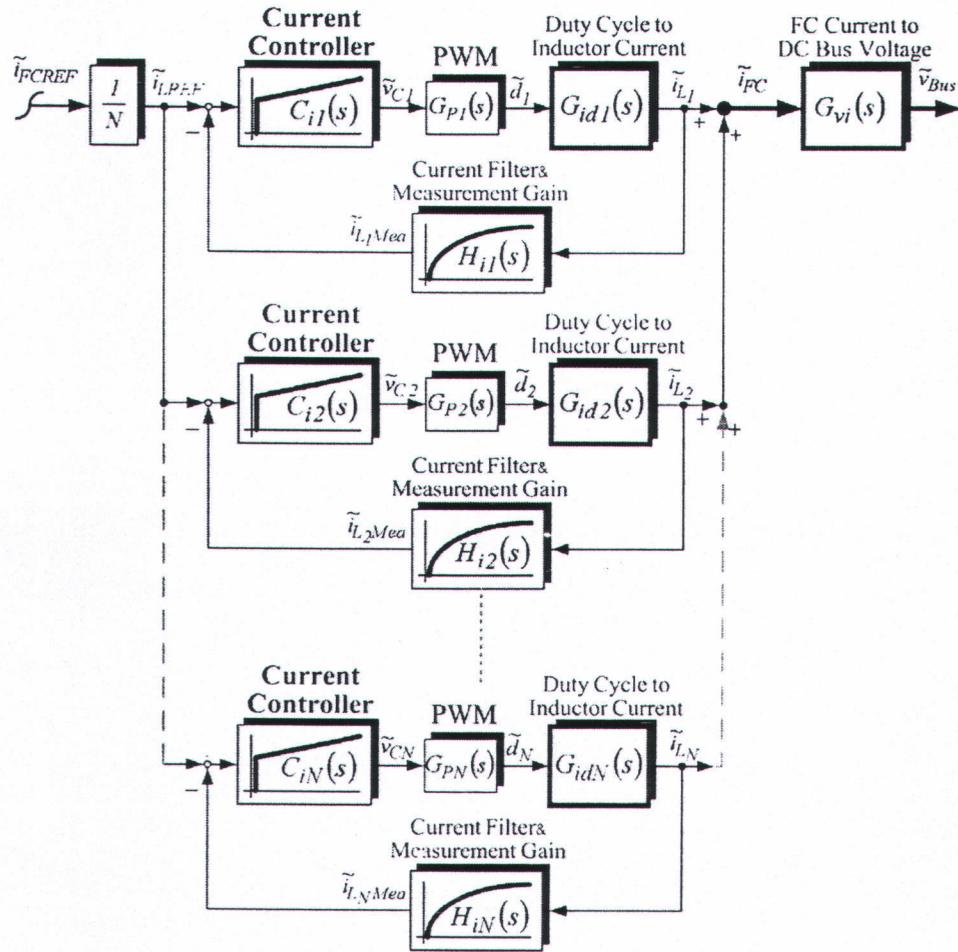


Fig. 5. Proposed FC current control loop of  $N$ -phase interleaved converter.

3. Experimental validation

3.1. Test bench description

The PEMFC test bench is presented in Figs. 6 and 7. The Nexa™ PEMFC system (1.2-kW, 46 A, around 26 V) was developed and commercialized by the Ballard Power Systems Inc. It is supplied using hydrogen from bottles under pressure, and with clean and dry air from a compressor. The design requirements and specifica-

tion of implemented power converters are detailed in Tables 1–4. The 2- and 4-phase power converters tested hereafter are illustrated in Figs. 8 and 9, respectively. Some guidelines of a boost power converter design can be seen in [8].

3.2. Control description

Measurement of each inductor current  $i_{L_i}$  is performed by means of a zero-flux Hall effect current sensor. Table 4 summarizes

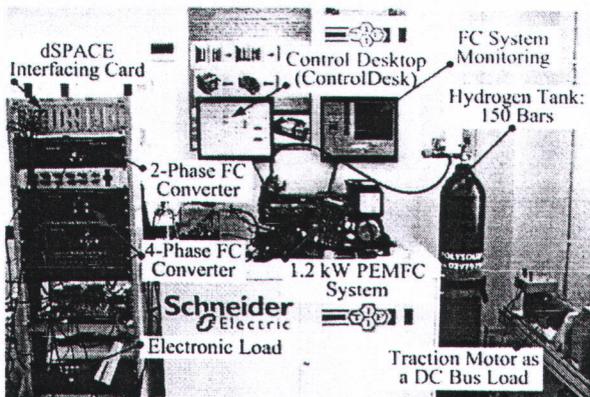


Fig. 6. PEMFC system test bench.

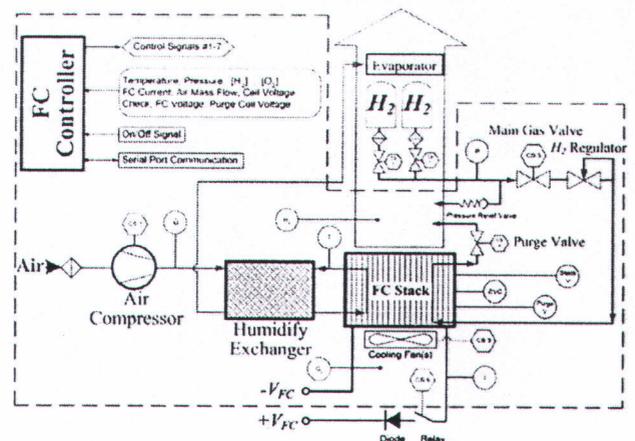


Fig. 7. Simplified functional block diagram of a Nexa™ PEMFC system.

**Table 1**  
Fuel cell converter design requirement.

Parameter	Value
Fuel cell rated power, $P_{FC\text{Rated}}$	1.2 kW
Fuel cell rated current, $I_{FC\text{Rated}}$	46 A
DC bus voltage, $V_{Bus}$	60 V
Full load efficiency, $\eta$	90%
Switching frequency, $f_s$	25 kHz

**Table 2**  
2-Phase parallel power converter specification.

Device	Specification
Power MOSFETs: $S_1$ and $S_2$	2 × IRFP264N (250 V, 38 A, 75 mΩ)
Diodes: $D_1$ and $D_2$	1 × RURG3020 (200 V, 30 A)
Input inductors: $L_1$ and $L_2$	2 × Double ferrite core E55 (216 μH, 33 turns, 1.1 mm of air-gap)
Output capacitor: $C_{Bus}$	2 × 3900 μF + 2 × 680 μF electrolytic (connected in parallel)

**Table 3**  
4-Phase parallel power converter specification.

Device	Specification
Power MOSFETs: $S_1, S_2, S_3$ and $S_4$	4 × IRFP264N (250 V, 38 A, 75 mΩ)
Diodes: $D_1, D_2, D_3$ and $D_4$	2 × RURG3020 (200 V, 30 A)
Input inductors: $L_1, L_2, L_3$ and $L_4$	4 × Double ferrite core E55 (396 μH, 43 turns, 1 mm of air-gap)
Output capacitor: $C_{Bus}$	2 × 3900 μF + 4 × 470 μF electrolytic (connected in parallel)

**Table 4**  
Inductor current control loop parameters.

Parameter	2-Phase converter	4-Phase converter
$V_{Bus\text{Rated}}$	60 V	60 V
$I_{L\text{Rated}}$	23 A	11.5 A
$D$	0.55	0.55
$K_i$	0.1	1.05
$T_{Ci}$	0.44 ms	0.61 ms
$K_f$	0.34 V A <sup>-1</sup>	1.2 V A <sup>-1</sup>
$T_f$	60 μs	15 μs

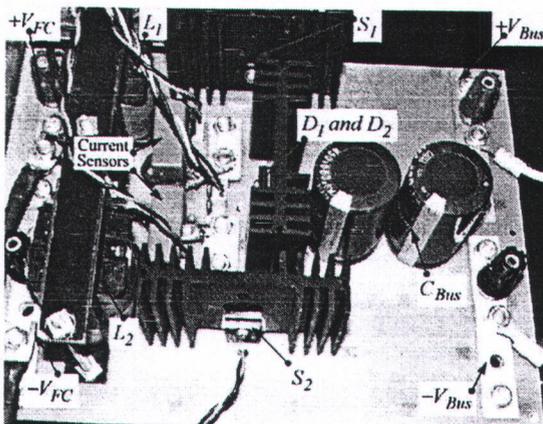


Fig. 8. 2-Phase step-up power converter in parallel.

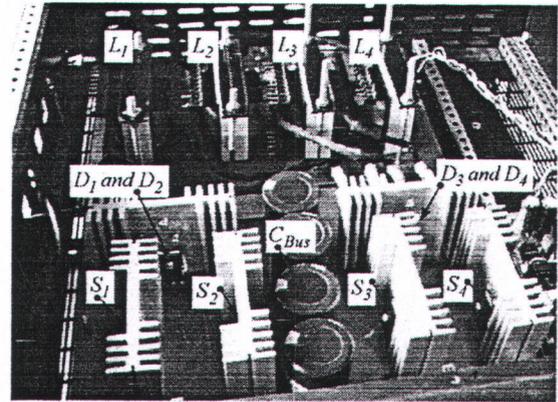


Fig. 9. 4-Phase step-up power converter in parallel.

the inductor current control loop parameters, which have been calculated in order to obtain a phase margin of about 55°. Some guidelines of the controller design in frequency domain can be seen in [8.22]. Each current regulator (proportional–integral controller) is set to virtually same values. The inductor current reference  $i_{L\text{REF}}$  is generated by the real time card dSPACE DS1104, through the mathematical environment of Matlab–Simulink and the ControlDesk software.

### 3.3. Experimental results

The experimental tests have been carried out by connecting the dc link to an adjustable resistor and an active load composed of a current reversible chopper, loaded by a dc servo motor coupled with a powder brake and a small flywheel. Then, the load at dc bus can be varied to the desired operating point by adjusting the load resistor and the powder motor brake.

#### 3.3.1. Fuel cell converters testing with an ideal power supply

Initial testing was operated by using an ideal 26-V power supply, which has the same rated voltage as the considered FC system, in order to confirm that the converters can operate correctly, and also to observe the dynamic performances of the inductor current control loops.

The oscilloscope waveforms in Figs. 10–12 depict the large-signal responses of the converters to an input current set-point step. Figs. 10 and 11 present the input current demand, the input current response, and the first and second inductor current responses of the 2-phase parallel converters. As for Fig. 12, it illustrates the input current demand, the input current response, and the first and third inductor current responses of the 4-phase parallel converters. One can observe that current responses of both converters have high dynamics with optimum response by the current compensator (PI controller). Absolutely, the input current is the sum of the inductor currents.

#### 3.3.2. Fuel cell converters testing with a Nexa™ PEMFC

The oscilloscope waveforms in Figs. 13–16 portray the steady-state characteristics of the interleaved converters at different FC current demands, the load at dc bus being adjusted in order to obtain a constant dc bus voltage of 60 V (rated dc bus voltage or operating point of the specification). Figs. 13 and 14 illustrate the FC current, and the first and second inductor currents of the 2-phase parallel converter at the average FC current reference of 4 A and 46 A (rated current), respectively. Fig. 15 presents the FC current, and the first, second and third inductor currents of the 4-phase parallel converters at the average FC current reference of 4 A.

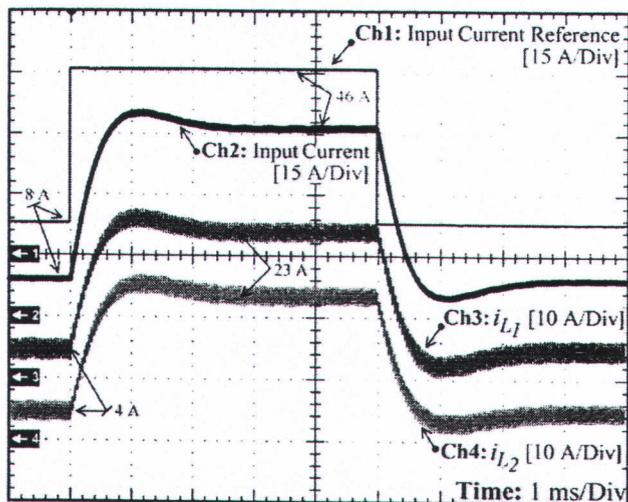


Fig. 10. Transient response of the 2-cell converter current loops to an input current reference step varying from 8 A to 46 A (rated current) and vice versa.

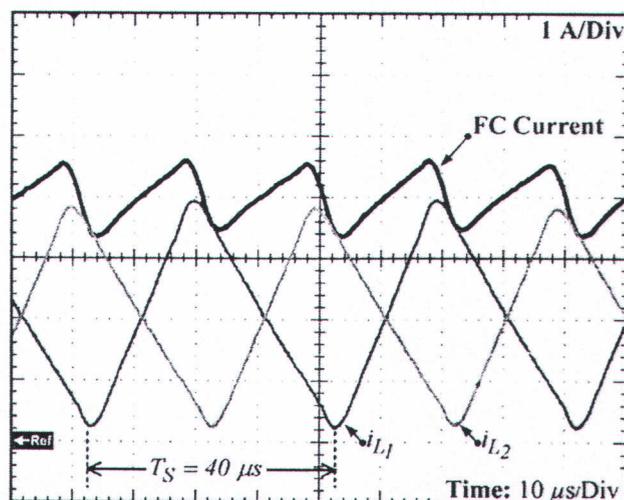


Fig. 13. Steady-state waveforms of the 2-cell interleaved converter system at a FC current reference of 4 A ( $v_{FC} = 35.8$  V).

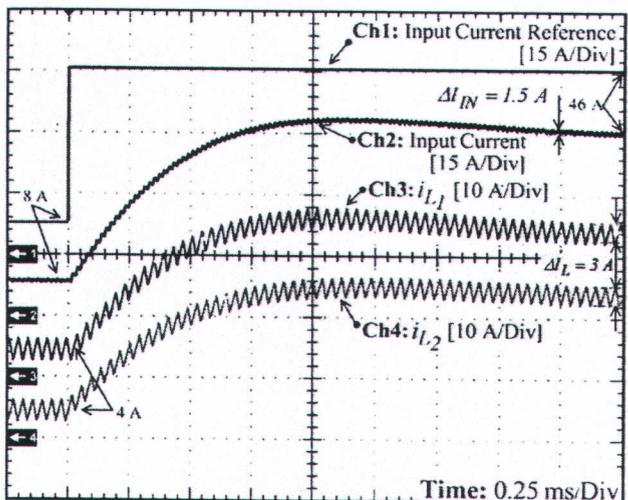


Fig. 11. Transient response of the 2-cell converter current loops to an input current reference step varying from 8 A to 46 A (rated current).

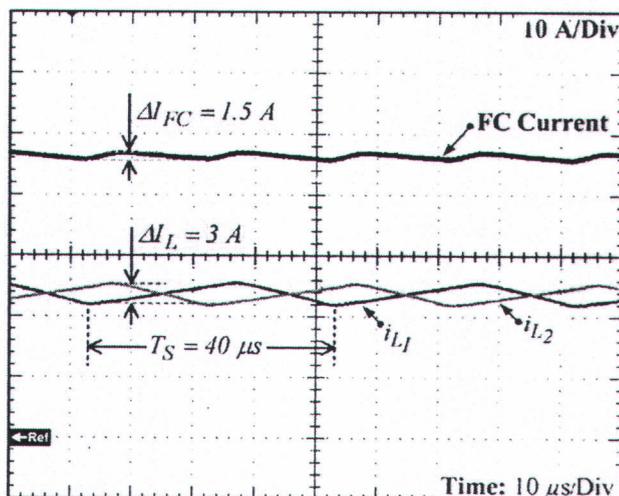


Fig. 14. Steady-state waveforms of the 2-cell interleaved converter system at a FC current reference of 46 A ( $v_{FC} = 26.3$  V).

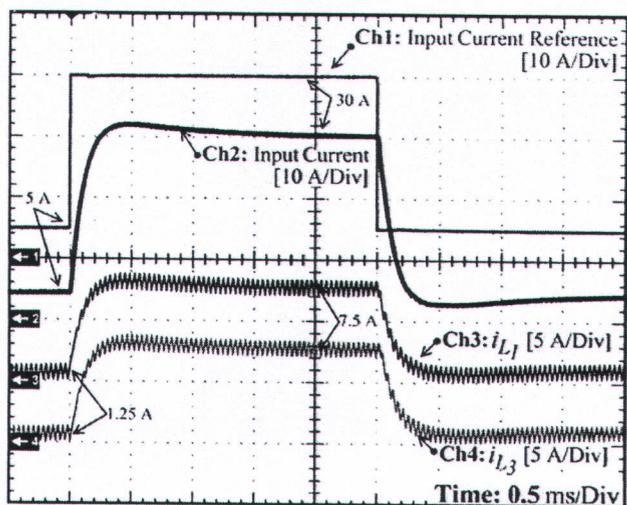


Fig. 12. Transient response of the 4-cell converter current loops to an input current reference step varying from 5 A to 30 A and vice versa.

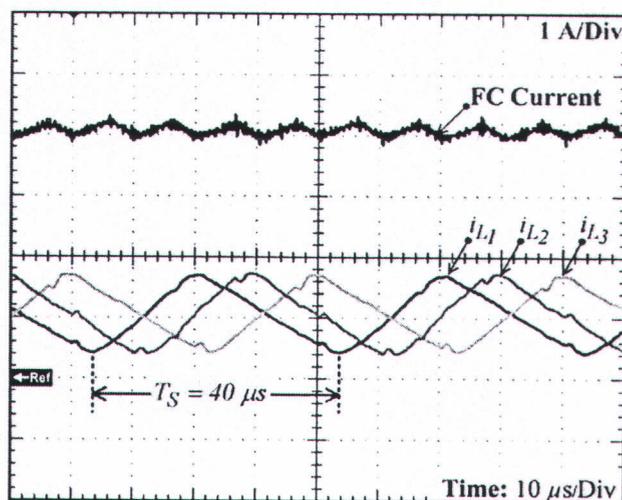


Fig. 15. Steady-state waveforms of the 4-cell interleaved converter system at a FC current reference of 4 A ( $v_{FC} = 35.8$  V).

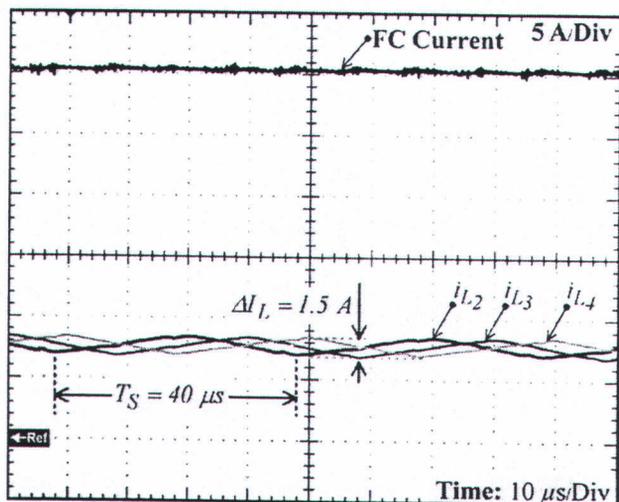


Fig. 16. Steady-state waveforms of the 4-cell interleaved converter system at a FC current reference of 30 A ( $v_{FC} = 28.9$  V).

And for the last test, Fig. 16 shows the FC current, and the second, third and fourth inductor currents of the 4-phase parallel converters at the average FC current reference of 30 A.

One can observe again that the FC current is the sum of the inductor currents, and that the FC ripple current is  $1/N$  the individual inductor ripple currents. Absolutely, the FC ripple current of the 4-cell interleaved converter is lower than the 2-cell interleaved converter. So, the FC ripple current of the 4-cell interleaved converter is nearly zero. It means that the FC mean current is close to the FC rms current. In addition, it can be seen the FC ripple frequency is  $N$ -times the switching frequency of 25-kHz.

#### 4. Conclusions

The main objective of this paper is to present the parallel converter modules with interleaving technique for a FC power source for high power applications. By this technique, ferrite core and Litz-wire size of inductors are simple to design and fabricate; and FC ripple current is reduced. The fact that it has fewer output capacitors is mostly due to lower output-ripple current, which results in lower cost and lower power dissipation. This circuit also significantly reduces the energy-storage requirement of the combined input inductors, thus reducing the magnetic volumes, heights, and dissipations. The multiphase approach reduced the overall power dissipation and spread that dissipation over a larger board area, allowing better thermal management. The main drawback of the multiphase approach is added circuit complexity, requiring measurement and balancing of each phase current as the larger number of control components illustrates.

The two non-isolated boost converters of 2-phase and 4-phase in parallel have been designed and implemented as a FC converter of 1.2-kW. So, the inductor average current control loops realized by analog circuits of paralleled converters are inevitable to share the same currents, and to control the FC current slope. Then, FC system is free of fuel starvation phenomenon, mechanical stresses in a FC system (fuel pressure, water pressure in tubes and stack) are reduced, and lifetime is improved.

Experimental results of implemented parallel converters connected with a Nexa™ PEMFC system (1.2-kW, 46-A) authenticate the excellent performances: static and dynamic states of the design system. Future works are to use the implemented parallel converters with interleaving algorithm to function in hybrid sources: FC/

Supercapacitor or FC/Li-Ion Battery or FC/Supercapacitor/Li-Ion Battery for a high power dc distributed generation system.

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#### References

- [1] Rajashekara K, Grieve J, Daggett D. Hybrid fuel cell power in aircraft. *IEEE Ind Appl Mag* 2008;14:54–60.
- [2] Corbo P, Migliardini F, Veneri O. Experimental analysis of a 20 kWe PEM fuel cell system in dynamic conditions representative of automotive applications. *Energy Convers Manage* 2008;49:2688–97.
- [3] Thounthong P, Davat B, Raël S. Drive friendly: fuel cell/supercapacitor hybrid power sources for future automotive power generation. *IEEE Power Energy Mag* 2008;6:69–76.
- [4] Thounthong P, Davat B, Raël S, Sethakul P. Fuel starvation. *IEEE Ind Appl Mag* 2009;15:52–9.
- [5] Ahmed NA, Miyatake M, Al-Othman AK. Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems. *Energy Convers Manage* 2008;49:2711–9.
- [6] Taniguchi A, Akita T, Yasuda K, Miyazaki Y. Analysis of electrocatalyst degradation in PEMFC caused by cell reversal during fuel starvation. *J Power Sources* 2004;130:42–9.
- [7] Thounthong P, Raël S, Davat B. Analysis of supercapacitor as second source based on fuel cell power generation. *IEEE Trans Energy Convers* 2009;24:247–55.
- [8] Thounthong P, Raël S, Davat B. Control algorithm of fuel cell and batteries for distributed generation system. *IEEE Trans Energy Convers* 2008;23:148–55.
- [9] Payman A, Pierfederici S, Tabar FM. Energy control of supercapacitor/fuel cell hybrid power source. *Energy Convers Manage* 2008;49:1637–44.
- [10] Andujar JM, Segura F, Vasallo M. A suitable model plant for control of the set fuel cell-DC/DC converter. *Renew Energy* 2008;33:813–26.
- [11] Agbossou K, Kolhe M, Hamelin J, Bose TK. Performance of a stand-alone renewable energy system based on energy storage as hydrogen. *IEEE Trans Energy Convers* 2004;19:633–40.
- [12] Mohr M, Fuchs FW. Comparison of three phase current source inverters and voltage source inverters linked with dc to dc boost converters for fuel cell generation systems. In: *Proceedings of the EPE'05*, 11–14 September, 2005. p. 1–10.
- [13] Wang C, Nehrir MH, Gao H. Control of PEM fuel cell distributed generation systems. *IEEE Trans Energy Convers* 2006;21:586–95.
- [14] De Bernardinis A, Péra MC, Garnier J, Hissel D, Coquery G, Kauffmann JM. Fuel cells multi-stack power architectures and experimental validation of 1 kW parallel twin stack PEFC generator based on high frequency magnetic coupling dedicated to on board power unit. *Energy Convers Manage* 2008; 49:2367–83.
- [15] Vilathgamuwa DM, Gajanayake CJ, Poh Chiang Loh. Modulation and control of three-phase paralleled Z-source inverters for distributed generation applications. *IEEE Trans Energy Convers* 2009;24:173–83.
- [16] Nam-Ju Park, Dong-Seok Hyun. IBC using a single resonant inductor for high-power applications. *IEEE Trans Industrial Electronics* 2009;56:1522–30.
- [17] Raggl K, Nussbaumer T, Doerig G, Biela J, Kolar JW. Comprehensive design and optimization of a high-power-density single-phase boost PFC. *IEEE Trans Industrial Electronics* 2009;56:2574–87.
- [18] Choe SY, Ahn JW, Lee JG, Baek SH. Dynamic simulator for a PEM fuel cell system with a PWM dc/dc converter. *IEEE Trans Energy Convers* 2008;23:669–80.
- [19] Trevisan D, Mattavelli P, Tenti P. Digital control of single-inductor multiple-output step-down dc–dc converters in ccm. *IEEE Trans Ind Electron* 2008;55:3476–83.
- [20] Wahdame B, Candusso D, François X, Harel F, Péra MC, Hissel D, et al. Analysis of a fuel cell durability test based on design of experiment approach. *IEEE Trans Energy Convers* 2008;23:1093–104.
- [21] Adzakpa KP, Agbossou K, Dubé Y, Dostie M, Fournier M, Poulin A. PEM fuel cells modeling and analysis through current and voltage transient behaviors. *IEEE Trans Energy Convers* 2008;23:581–91.
- [22] Thounthong P, Raël S, Davat B. Control strategy of fuel cell and supercapacitors association for distributed generation system. *IEEE Trans Ind Electron* 2007;54:3225–33.

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# Modeling and Control of Fuel Cell/Supercapacitor Hybrid Source Based on Differential Flatness Control

Phatiphat Thounthong, *Member, IEEE*, Serge Pierfederici, Jean-Philippe Martin, Melika Hinaje, and Bernard Davat, *Member, IEEE*

**Abstract**—Fuel-cell vehicles (FCVs) with energy storage (ES) device(s) could result in improved lifetime, performance, fuel economy, and reduced cost. This paper presents the utilization of an ES device consisting of a supercapacitor bank for future electric vehicles with a hydrogen fuel cell (FC) as the main power source. The study mainly focuses on the innovative control law based on the flatness properties for a FC/supercapacitor hybrid power source. Utilizing the flatness principle, we propose simple solutions to the hybrid energy-management and stabilization problems. A supercapacitor module, as a high dynamic and high-power density device, functions to supply energy to regulate the dc-bus energy. The FC, as a slower dynamic source in this system, functions by supplying energy to keep the supercapacitor module charged. To ensure energy-efficient operation of the FC stack, the output current ripple of the FC stack is minimized by parallel boost converters with an interleaving switching technique for a high-frequency ripple by the supercapacitor for a low-frequency ripple. To authenticate the proposed control laws, a test bench is realized in the laboratory. The control algorithm (energy and current control loops) is digitally implemented by dSPACE controller DS1103. Experimental results with small-scale devices (a proton exchange membrane FC (PEMFC) of 500 W, 50 A, and 10 V and a supercapacitor bank of 250 F, 32 V, and 500 A) substantiate the excellent performance during load cycles.

**Index Terms**—Converters, current control, electric vehicles, fuel cells (FCs), nonlinear, supercapacitor.

## I. INTRODUCTION

AT THE MOMENT, hydrogen fuel-cell (FC) vehicle technology is receiving extensive consideration as a strategy

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to decrease oil consumption and reduce destructive emissions. There are many different types of FCs, with the principal differences between them being the type of electrolyte and/or the type of fuel that they use. One of the most promising FCs to be employed in vehicle applications is the proton exchange membrane FC (PEMFC) because of its relatively small size, lightweight nature, and ease of construction. Nevertheless, the cost, transient response, and cold performance of PEMFC systems may present significant challenges to the extensive adoption of the technology for transportation in the near future [1], [2].

According to recent works on the FC characteristics [3], [4], they point out the specific properties of FCs that their output power response is delayed because of processing time through subsidiary equipment, i.e., their slow internal electrochemical and thermodynamic characteristics. Therefore, to supply electric power to fluctuating loads by the hybrid system of the FC, an electric energy-storage (ES) system is needed to compensate the gap between the output from the FC and the load, in addition to the collaborative load balancing [5], [6].

Previous research has shown that FC hybridization with a battery [7], [8], with a supercapacitor (ultracapacitor) [9], and with a battery/supercapacitor [10]–[12], provides cost, performance, and operational improvements, as well as fuel economy benefits that are attractive and should be considered. Among the present preproduction hybrid FC vehicles, the Toyota FCHV has a nickel-metal hydride ES system similar to that of the Toyota Prius, and the Honda FCX-V4 uses a supercapacitor bank that provides regenerative braking and power-assist capability.

Control, robustness, stability, efficiency, and optimization of hybrid sources remain an essential area of research. Several researchers have studied the different topologies. Schaltz *et al.* [13] studied two energy-management strategies of a FC/battery/supercapacitor hybrid power source for vehicle applications. Feroldi *et al.* [14] studied the control based on efficiency map of an FC/supercapacitor hybrid power source for vehicle applications. Muyeen *et al.* [15] studied the control based on fuzzy logic of a wind turbine/supercapacitor hybrid power source. Uzunoglu and Alam [16] studied the control based on the wavelet-based load sharing algorithm of an FC/supercapacitor hybrid power source. Thounthong *et al.* studied a regulated dc-bus voltage FC/supercapacitor hybrid source (based on a basic linear controller by setting controller parameters depending on the defined operating point) [17], a regulated dc-bus voltage FC/battery/supercapacitor hybrid source (based on a basic

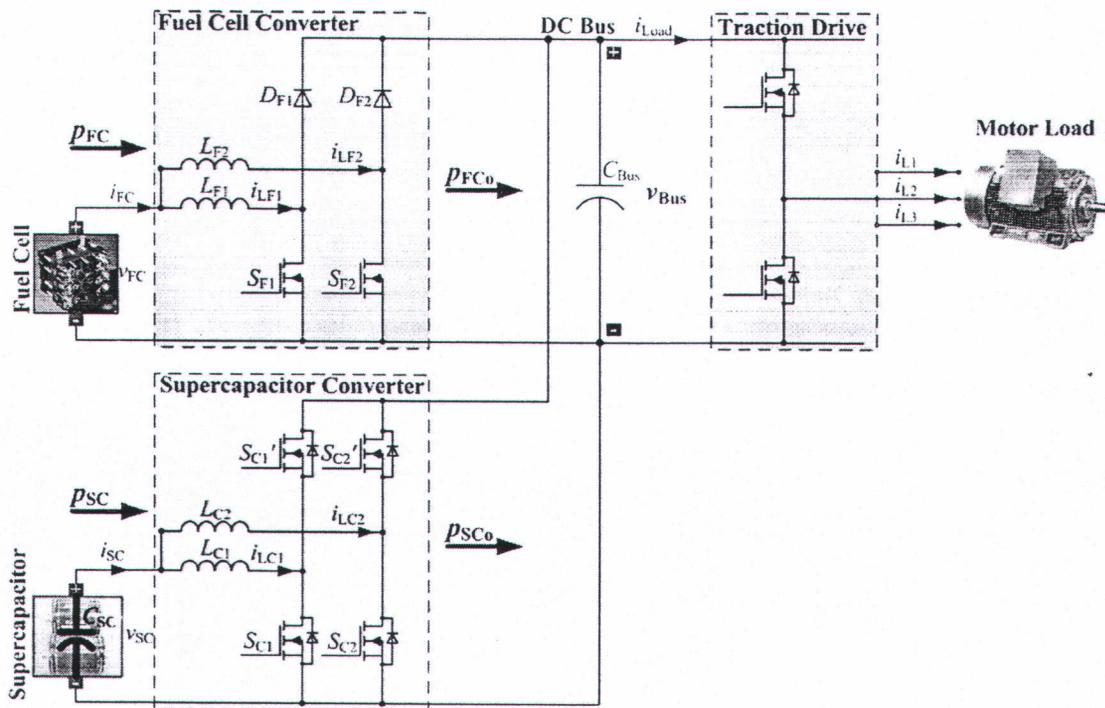


Fig. 1. Topology of a multiconverter-based hybrid power-management system, where  $p_{\text{Load}} (= v_{\text{Bus}} \times i_{\text{Load}})$ ,  $v_{\text{Bus}}$ , and  $i_{\text{Load}}$  are the load power, the dc-bus voltage, and the dc-bus load current, respectively.  $p_{\text{FC}} (= v_{\text{FC}} \times i_{\text{FC}})$ ,  $v_{\text{FC}}$ , and  $i_{\text{FC}}$  are the FC power, voltage, and current, respectively.  $p_{\text{SC}} (= v_{\text{SC}} \times i_{\text{SC}})$ ,  $v_{\text{SC}}$ , and  $i_{\text{SC}}$  are the supercapacitor power, voltage, and current, respectively.  $p_{\text{FC}0}$  and  $p_{\text{SC}0}$  are the output powers to the dc link from the converters of FC and supercapacitor, respectively.

linear controller by setting controller parameters depending on the defined operating point [11], and an unregulated dc-bus voltage FC/battery hybrid source (based on the battery state of charge) [18].

This paper presents the original control method based on the flatness properties for the FC hybrid power source. It will provide a significant contribution to the field of the multisource system, particularly in nonlinear power electronics applications. In Section II, the FC and supercapacitor converter structure of multiphase power converters is presented in detail, including their current control loops, as well as a hybrid reduced-order model. The proposed control laws based on the differential flatness properties will be explained in detail in Section III. In Section IV, experimental results will show the system performance during load cycles. The summary and conclusions are presented in Section V.

## II. HYBRID POWER SOURCE

### A. Power Converter Structure

An FC generator and a storage device need to be interfaced through power electronic converters [19], [20]. Different power electronic circuits have been proposed in recent work to interface the different energy sources with the distributed system [21], [22]. Normally, an FC system needs a boost dc/dc converter (step-up converter) to adapt the FC output voltage to the desired dc utility voltage level and smooth the FC supply current [21]. In addition, a storage de-

vice needs a bidirectional dc/dc converter (two-quadrant converter) [23].

Nevertheless, a single converter will be limited when the power increases or for higher step-up ratios. That way, the use of paralleling power converters with the interleaved technique may offer better performance [21]. One proposes a power-electronics topology for the hybrid power-management system, as shown in Fig. 1, in which multiphase dc/dc converters are connected at the output of the stack and the storage device, which are then connected in parallel to share the load at the dc bus. The number of parallel converter modules  $N$  (with interleaving switching technique [21]) would depend upon the rated power of the stack and the supercapacitor module. Here,  $N$  is equal to 2 for the FC and supercapacitor converters (called two-phase converters).

For safety and high dynamics, the FC and supercapacitor converters are mostly controlled by inner current regulation loops, classically [2], [24]. The current controls of these converters, as illustrated in Fig. 2, are similar to a basic current control of parallel converters. Here, sliding-mode current control is implemented for each converter module. The dynamics of the current regulation loops are also supposed to be much faster than those of the outer control loops. These current control loops are supplied by two reference signals: 1) the supercapacitor current reference  $i_{\text{SCREF}}$  and 2) the FC current reference  $i_{\text{FCREF}}$ , generated by the energy-management algorithm presented hereafter. Thus, the currents  $i_{\text{SC}}$  and  $i_{\text{FC}}$  are considered to follow their references  $i_{\text{SCREF}}$  and  $i_{\text{FCREF}}$  completely [25].

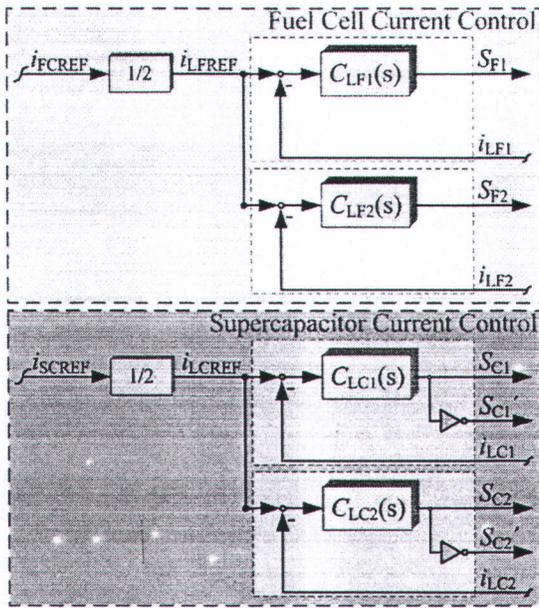


Fig. 2. Current control loops of the proposed FC/supercapacitor converters.

### B. Modeling of the Hybrid Power Source

One supposes that the FC and supercapacitor currents follow their set-point values perfectly. Thus

$$i_{FC} = i_{FCREF} = \frac{p_{FC}}{v_{FC}} = \frac{p_{FCREF}}{v_{FC}} \quad (1)$$

$$i_{SC} = i_{SCREF} = \frac{p_{SC}}{v_{SC}} = \frac{p_{SCREF}}{v_{SC}} \quad (2)$$

Now, the FC generator and the supercapacitor storage device function as controlled current sources. We consider here that there are only static losses in these converters (called *reduced-order model*), and  $r_{FC}$  and  $r_{SC}$  represent the static losses in the FC and supercapacitor converters (refer to Fig. 1), respectively.

The dc-bus capacitive energy  $y_{Bus}$  and the supercapacitive energy  $y_{SC}$  can be written as

$$y_{Bus} = \frac{1}{2} C_{Bus} v_{Bus}^2 \quad (3)$$

$$y_{SC} = \frac{1}{2} C_{SC} v_{SC}^2 \quad (4)$$

The total electrostatic energy  $y_T$  stored in the dc-bus capacitor  $C_{Bus}$  and in the supercapacitor  $C_{SC}$  can also be written as

$$y_T = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2 \quad (5)$$

The dc-bus capacitive energy  $y_{Bus}$  is given versus  $p_{FCo}$ ,  $p_{SCo}$ , and  $p_{Load}$  by the following differential equation:

$$\dot{y}_{Bus} = p_{FCo} + p_{SCo} - p_{Load} \quad (6)$$

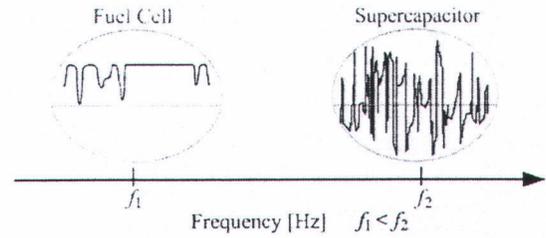


Fig. 3. Dynamic classification of the embedded sources in frequency space.

where

$$p_{FCo} = p_{FC} - r_{FC} \left( \frac{p_{FC}}{v_{FC}} \right)^2 \quad (7)$$

$$p_{SCo} = p_{SC} - r_{SC} \left( \frac{p_{SC}}{v_{SC}} \right)^2 \quad (8)$$

$$p_{Load} = v_{Bus} \cdot i_{Load} = \sqrt{\frac{2y_{Bus}}{C_{Bus}}} \cdot i_{Load} \quad (9)$$

$$p_{SC} = v_{SC} \cdot i_{SC} = \sqrt{\frac{2y_{SC}}{C_{SC}}} \cdot i_{SC} \quad (10)$$

### III. ENERGY MANAGEMENT AND CONTROL LAWS

As mentioned earlier, one must operate an FC at slow dynamics to improve its stack lifetime [2], [4]. Then, it can be compensated by faster dynamics from storage devices. The energy-management strategy based on a dynamic classification aims at distributing the global power mission of the vehicle into sources in such a way that each source is optimally used. According to the two points mentioned previously, embedded energy sources can be classified in frequency space, as illustrated in Fig. 3. The FC generator is controlled as a lower dynamic power source. The supercapacitor is a higher dynamic power source, which provides the microcycles and the fast dynamic power supply.

In this kind of system, as depicted in Fig. 1, there are two voltage variables or two energy variables to be regulated.

- 1) The dc-bus energy  $y_{Bus}$  is the most important variable.
- 2) It is the supercapacitor storage energy  $y_{SC}$  (charging supercapacitor).

Therefore, the proposed hybrid energy management is that its basic principle lies in using the supercapacitors (the faster energy source) to supply the energy required to achieve dc-bus voltage regulation (or dc-bus energy regulation) [2]. Then, the FC, although obviously the main energy source of the system, functions as the generator (with dynamic limitations at  $f_1$ ) that supplies energy for both the dc-bus capacitor  $C_{Bus}$  and the supercapacitors  $C_{SC}$  to keep them charged.

#### A. Literature Review: Control System Based on Differential Flatness Theory

The idea of differential flatness theory was first introduced by Fliess *et al.* [26] (see the Appendix). This allowed an alternate representation of the system where trajectory planning and nonlinear controller design is clear cut. The advantages of the

differential flatness approach are that the trajectories of the system are straightforwardly estimated by the trajectories of a flat output and its derivatives without integrating any differential equation. Currently, these ideas have lately been used in a variety of nonlinear systems across various engineering disciplines, including the following:

- 1) process of stirred tank chemical reactor [27];
- 2) vehicle steering control [28];
- 3) control of a high-speed linear axis driven by pneumatic muscle actuators [29];
- 4) control of cathode pressure and oxygen excess ratio of a PEMFC system [30];
- 5) steering control of a two-level quantum system [31];
- 6) reactive power and dc voltage tracking control of a three-phase voltage source converter [32];
- 7) control of open-channel flow in an irrigation canal [33];
- 8) current control for three-phase three-wire boost converters [34];
- 9) design of a guidance algorithm for the hypersonic phase of a lifting-body vehicle [35];
- 10) control of space robot with arbitrarily oriented joint axes and two momentum wheels at the base [36].

### B. DC-Bus Energy Regulation

To prove that the system is flat, the dc-bus electrostatic energy  $y_{Bus}$  stored in  $C_{Bus}$  is assumed as the flat output component. Therefore, one defines a flat output  $y_1 = y_{Bus}$ , a control variable  $u_1 = p_{SCLIMITED}$ , and a state variable  $x_1 = v_{Bus}$ . From (3), the state variable  $x_1$  can be written as

$$x_1 = \sqrt{\frac{2y_1}{C_{Bus}}} = \varphi_1(y_1). \quad (11)$$

From (6), the control variable  $u_1$  can be calculated from the flat output  $y_1$  and its time derivatives (*inverse dynamics*; see Fig. 12) as

$$u_1 = 2 \cdot P_{SCLIMITED} \cdot \left[ 1 - \sqrt{1 - \left( \frac{\dot{y}_1 + \sqrt{\frac{2y_1}{C_{Bus}}} \cdot i_{Load} - p_{FCO}}{P_{SCLIMITED}} \right)^2} \right] \\ = \psi_1(y_1, \dot{y}_1) = p_{SCLIMITED} \quad (12)$$

where

$$P_{SCLIMITED} = \frac{v_{SC}^2}{4r_{SC}}. \quad (13)$$

$P_{SCLIMITED}$  is the limited maximum power from the supercapacitor module.

Therefore, it is apparent that  $x_1 = \varphi_1(y_1)$  and  $u_1 = \psi_1(y_1, \dot{y}_1)$  correspond with (A-6) and (A-7). Consequently, the proposed reduced-order model of the hybrid system can be considered as a flat system.

A desired reference trajectory for the dc-bus energy is represented by  $y_{1REF}$ . A feedback control law (see Fig. 12)

achieving an exponential asymptotic tracking of the trajectory is given by the following expression [23], [37]:

$$(\dot{y}_1 - \dot{y}_{1REF}) + K_{11}(y_1 - y_{1REF}) + K_{12} \int (y_1 - y_{1REF}) d\tau = 0 \quad (14)$$

where the set of controller parameters  $(K_{11}, K_{12})$  is chosen so that the roots of the closed-loop characteristic polynomial in the complex variable  $s$

$$p(s) = s^2 + \lambda_1 s^1 + \lambda_0 \quad (15)$$

is a Hurwitz polynomial.

Obviously, the tracking error  $e_1 = y_1 - y_{1REF}$  satisfies

$$\ddot{e}_1 + K_{11}\dot{e}_1 + K_{12}e_1 = 0. \quad (16)$$

An optimum choice of the design controller parameters is obtained by matching the characteristic polynomial  $p(s)$  to a desired characteristic polynomial with defined root locations.

One may set as a desired characteristic polynomial

$$p(s) = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (17)$$

$$K_{11} = 2\zeta\omega_n \quad (18)$$

$$K_{12} = \omega_n^2 \quad (19)$$

where  $\zeta$  and  $\omega_n$  are the desired dominant damping ratio and the natural frequency, respectively.

It is noticeable that the control system is stable for  $K_{11}, K_{12} > 0$  ( $\zeta, \omega_n > 0$ ). However, based on the power-electronic constant switching frequency  $f_S$  and the cascade control structure, the outer control loop (here the dc-bus energy control) must operate at a cutoff frequency  $f_E \ll f_C$  (a cutoff frequency of the supercapacitor current loop)  $\ll f_S$  [38]. Once the flat outputs are stabilized, the whole system is stable because all the variables of the system are expressed in terms of the flat outputs via (11)–(13).

### C. Supercapacitive Energy Regulation

For total energy regulation (or supercapacitor energy regulation), a desired reference trajectory for the total energy is represented by  $y_{TREF}$ . Since the supercapacitor ES is an enormous size capacity, and the supercapacitor energy is defined as a slower dynamic variable than the dc-bus energy variable, a special control law of the total energy regulation is defined as

$$p_{FCDem} = P_{FCMin}, \quad \text{if } y_{TREF} - y_T < -\Delta y \quad (20)$$

$$p_{FCDem} = \frac{f(p_{FC}, p_{Load}) - P_{FCMin}}{\Delta y} \cdot (y_{TREF} - y_T) \\ + f(p_{FC}, p_{Load}), \quad \text{if } -\Delta y < y_{TREF} - y_T \leq 0 \quad (21)$$

$$p_{FCDem} = \frac{P_{FCMax} - f(p_{FC}, p_{Load})}{\Delta y} \cdot (y_{TREF} - y_T) \\ + f(p_{FC}, p_{Load}), \quad \text{if } 0 < y_{TREF} - y_T \leq \Delta y \quad (22)$$

$$p_{FCDem} = P_{FCMax}, \quad \text{if } \Delta y < y_{TREF} - y_T \quad (23)$$

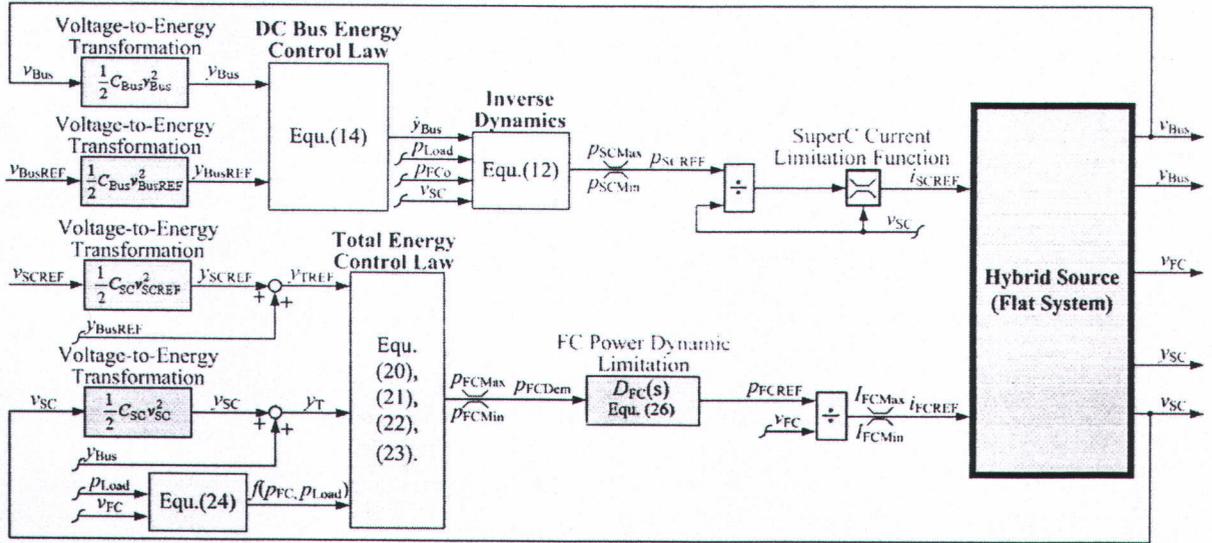


Fig. 4. Proposed control scheme for the FC/supercapacitor hybrid source.

where

$$f(p_{FC}, p_{Load}) = 2 \cdot P_{FCLimited} \left( 1 - \sqrt{1 - \frac{p_{Load}}{P_{FCLimited}}} \right) \quad (24)$$

$$P_{FCLimited} = \frac{v_{FC}^2}{4 \cdot r_{FC}} \quad (25)$$

$P_{FCLimited}$  is the limited maximum power from the FC converter.  $P_{FCMax}$  and  $P_{FCMin}$  are the maximum and minimum power of the FC stack, respectively.  $\Delta y$  is the regulation parameter.

The total energy control law generates the FC power demand  $p_{FCDem}$  [see (20)–(23)]. The FC, although clearly the main energy source of the system, functions as the generator that supplies energy for both the dc-bus capacitor  $C_{Bus}$  and the supercapacitors  $C_{SC}$  to keep them charged.

#### D. Conclusion of the Control Laws

The multivariable control of the FC/supercapacitor hybrid power source previously detailed is portrayed in Fig. 4. The dc-bus energy control law generates a supercapacitor power reference  $p_{SCREF}$  [or the control variable  $u_1$ ; see (12)]. This signal is then divided by the measured supercapacitor voltage  $v_{SC}$  and limited to maintain the supercapacitor voltage within an interval  $[V_{SCMin}, V_{SCMax}]$  by limiting a supercapacitor charging current or discharging current, as presented in the block “SuperC Current Limitation Function” [17]. This results in the supercapacitor current reference  $i_{SCREF}$ . For the total energy control law [see (20)–(25)], it generates the FC power demand  $p_{FCDem}$ . It must be limited in slope, which enables the safe operation of the FC with respect to the dynamic constraints that are associated with the FC stack, as portrayed in Fig. 3. To obtain a natural linear function, a second-order delay (filter)  $D_{FC}(s)$  is chosen for the limited FC power dynamics as

$$D_{FC}(s) = \frac{p_{FCREF}(s)}{p_{FCDem}(s)} = \frac{1}{\left(\frac{s}{\omega_{n1}}\right)^2 + \frac{2\zeta_1}{\omega_{n1}}s + 1} \quad (26)$$

where  $\omega_{n1}$  and  $\zeta_1$  are the regulation parameters. Then, the FC power reference  $p_{FCREF}$  is divided by the measured FC voltage  $v_{FC}$ . This results in an FC current reference  $i_{FCREF}$ . For safety, the FC current reference  $i_{FCREF}$  must be limited in level, i.e., within an interval [maximum FC current  $I_{FCMax}$  (corresponding to a FC rated current), minimum FC current  $I_{FCMin}$  (set to 0 A)].

## IV. PERFORMANCE VALIDATION

### A. Test Bench Explanation

To authenticate the proposed innovative control laws of the hybrid system, the small-scale test bench was implemented in a laboratory, as illustrated in Fig. 5. The PEMFC system (500 W, 50 A, 10 V) was achieved by the Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW) society. It consists of 16 cells of 100 cm<sup>2</sup> in series, as illustrated in Fig. 5. It is supplied using pure hydrogen from an aluminum tank under pressure of 150 bars and with clean and dry air from a compressor (50 W). The supercapacitor bank is obtained by means of two supercapacitor modules BMOD0500-P016 (developed and manufactured by Maxwell Technologies Inc.: 500 F, 16 V, 500 A) connected in series. The test bench was operated at around 25 °C at room temperature.

The FC converter (two-phase parallel boost converters) and the supercapacitor converter (two-phase parallel bidirectional converters) (see Fig. 1) are realized in the laboratory. The converter parameters and the semiconductor components are detailed in Table I.

### B. Control Description

Measurements of the FC current  $i_{FC}$ , the supercapacitor current  $i_{SC}$ , the load current  $i_{Load}$ , the dc-bus voltage  $v_{Bus}$ , the FC voltage  $v_{FC}$ , and the supercapacitor voltage  $v_{SC}$  are carried out by means of zero-flux Hall effect sensors. The two energy control loops and the two current control loops have

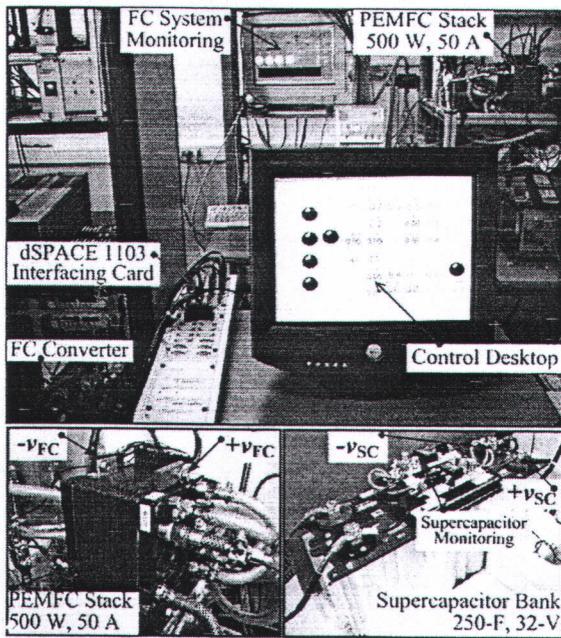


Fig. 5. Test bench system at the Groupe de Recherche en Electrotechnique et Electronique de Nancy (GREEN).

TABLE I  
CONVERTER PARAMETERS AND SEMICONDUCTOR DEVICES

Fuel Cell Converter:		
Inductors $L_{F1}=L_{F2}$	35	$\mu\text{H}$
MOSFETs $S_{F1}=S_{F2}$	IXFN230N10: 100 V, 230 A	
Schottky diode $D_{F1}=D_{F2}$	STPS160H100TV: 100 V, 80 A	
Supercapacitor Converter:		
Inductors $L_{C1}=L_{C2}$	140	$\mu\text{H}$
MOSFETs $S_{C1}=S_{C2}$	STE110NS20FD: 200 V, 110 A	
$=S_{C1}'=S_{C2}'$		

TABLE II  
DC-BUS ENERGY CONTROL LOOP PARAMETERS

$V_{\text{BusREF}}$	42	V
$C_{\text{Bus}}$	6200	$\mu\text{F}$
$K_{11}$	424	$\text{rad}\cdot\text{s}^{-1}$
$K_{12}$	$90 \times 10^3$	$\text{rad}^2\cdot\text{s}^{-2}$
$r_{\text{FC}}$	0.015	$\Omega$
$r_{\text{SC}}$	0.030	$\Omega$
$P_{\text{SCMax}}$	+1500	W
$P_{\text{SCMin}}$	-1500	W
$V_{\text{SCMax}}$	32	V
$V_{\text{SCMin}}$	12.5	V
$I_{\text{SCRated}}$	100	A

been implemented in a real time card dSPACE DS1103 through the mathematical environment of MATLAB/Simulink with a sampling frequency of 25 kHz.

The parameters associated with the dc-bus energy regulation loop and the total energy regulation loop are shown in Tables II and III, respectively. The parameters for the FC power dynamic delay are shown in Table III. This value has experimentally been determined as the highest power slope of our FC system, where no fuel starvation occurs. It must be noted here that, for

TABLE III  
TOTAL ENERGY CONTROL LOOP PARAMETERS

$V_{\text{SCREF}}$	25	V
$C_{\text{SC}}$	250	F
$\Delta y$	$6.25 \times 10^3$	J
$r_{\text{FC}}$	0.015	$\Omega$
$P_{\text{FCMax}}$	320	W
$P_{\text{FCMin}}$	0	W
$I_{\text{FCMax}}(\text{Rated})$	50	A
$I_{\text{FCMin}}$	0	A
$\zeta_1$	1	
$\omega_{n1}$	0.5	$\text{rad}\cdot\text{s}^{-1}$

the small-test bench, the FC maximum power  $P_{\text{FCMax}}$  is set at 320 W; in fact, the rated FC power considered here is 500 W.

### C. Experimental Results

The experimental tests have been carried out by connecting the dc bus loaded by an electronic active load. Figs. 6 and 7 present waveforms that are obtained during the load cycles (motoring and regenerative braking modes). It shows the dc-bus voltage, the FC voltage, the load power, the supercapacitor power, the FC power, the supercapacitor current, the FC current, and the supercapacitor voltage (or the supercapacitor state of charge *SOC*).

As illustrated in Fig. 6, the initial state is in no-load power, and the storage device is full of charge, i.e.,  $v_{\text{SC}} = 25$  V. As a result, both FC and supercapacitor powers are zero. At  $t = 10$  s, the load power steps to the final value of around +720 W (imitated vehicle acceleration). Synchronously, the final FC power increases with a limited slope (second order characteristics) to a limited maximum power of 320 W. Thus, the supercapacitor, which supplies most of the power that is required during stepped load, remains in a discharge state after constant power because the steady-state load power is greater than the FC limited maximum power. After that, at  $t = 70$  s, the load power steps from +720 to +100 W. Now, the supercapacitor voltage is equal to around 18.5 V; as a result, the supercapacitor is changing its state from discharging to charging. The FC power is still at the limited maximum power of 320 W to supply the energy to the load and to charge the supercapacitor.

As illustrated in Fig. 7, in the initial state, the load power is equal to +80 W, and the supercapacitor voltage is equal to 24.5 V, which is nearly fully charged. As a result, the FC power is 120 W to supply the energy for the load and to charge the supercapacitor. At  $t = 10$  s, the load power steps to -400 W (imitated vehicle deceleration or regenerative braking), and the supercapacitor is deeply charged (recuperative braking energy), demonstrating the two phases.

- 1) First, the supercapacitor recovers the energy that is supplied to the dc bus by the FC and the load; synchronously, the FC power reduces with a limited slope (second-order characteristics) to zero.
- 2) Second, at  $t = 20$  s, the supercapacitor absorbs the negative energy supplied only by the load. As a result, the supercapacitor is overcharged, i.e.,  $v_{\text{SC}} > v_{\text{SCREF}} = 25$  V.

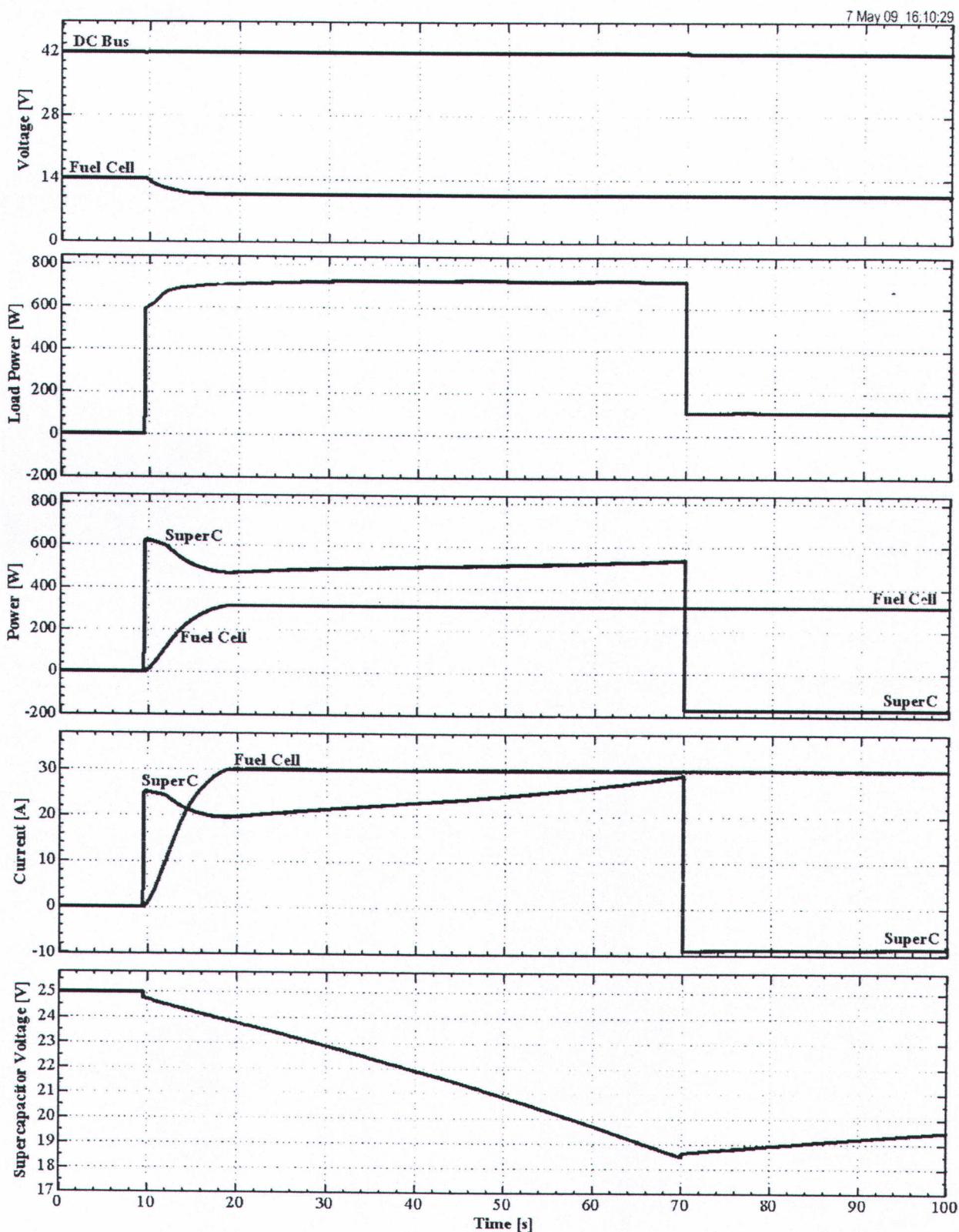


Fig. 6. Hybrid source response during step load from 0 to 720 W and from 720 to 100 W (motoring mode).

After that, at  $t = 60$  s, the load power steps from  $-400$  to  $+80$  W. Now, the supercapacitor voltage is equal to around 27 V (overcharged). As a result, the supercapacitor changes

its state from charging to discharging. The FC power is still at the limited minimum power of 0 W. Therefore, the load power is supplied by only the supercapacitor power. After that, when

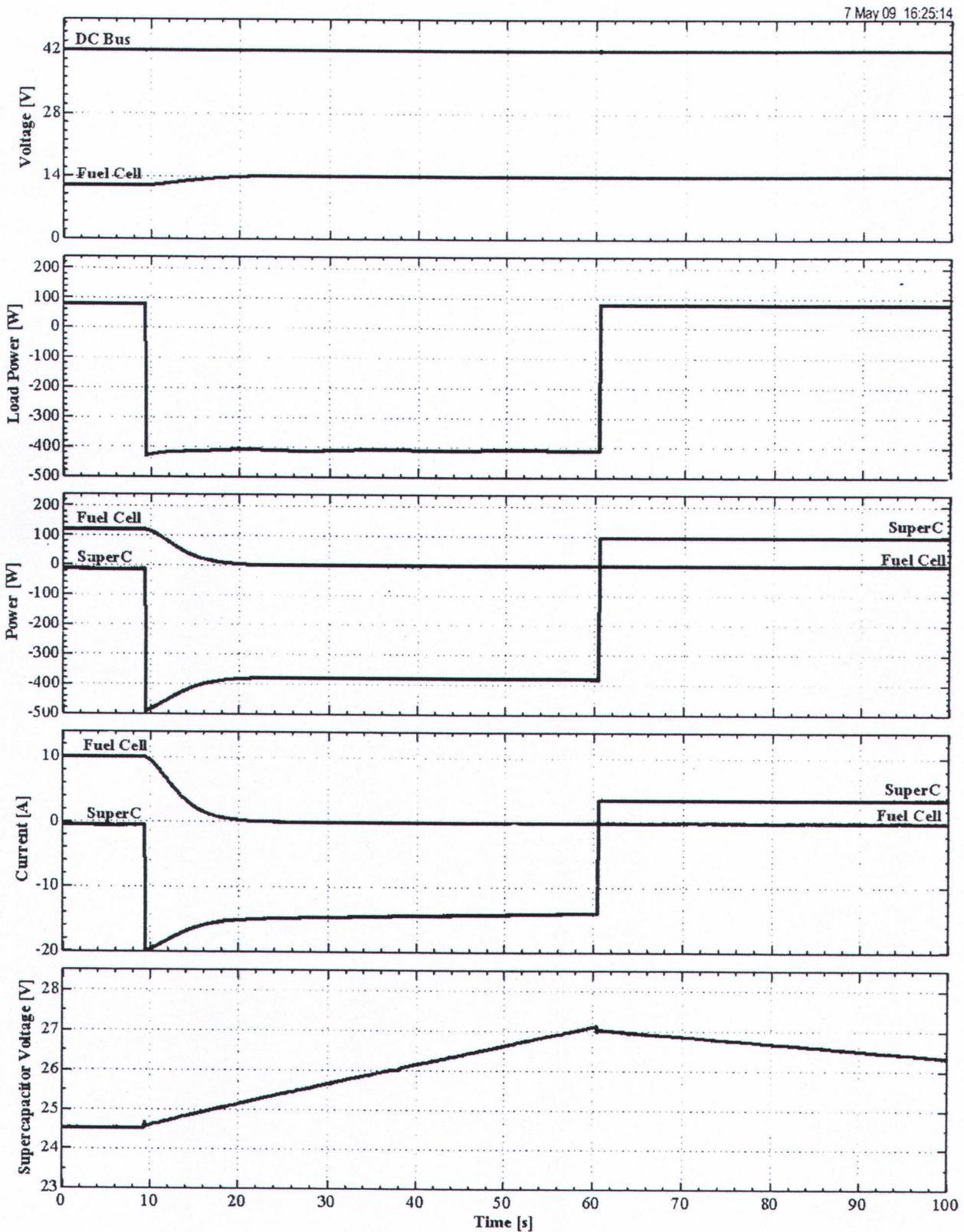


Fig. 7. Hybrid source response during step load from +80 to -400 W and from -400 to +80 W (regenerative braking mode).

$v_{SC}$  reduces to  $v_{SCREF}$  of 25 V, the supercapacitor power will reduce to zero, and the FC power will increase to supply the energy for the load.

To illustrate the dynamic regulation of the dc-bus energy (voltage), the oscilloscope waveforms in Fig. 8 portray the dc-bus voltage (representing the flat output  $y_1$ ) dynamics at a high

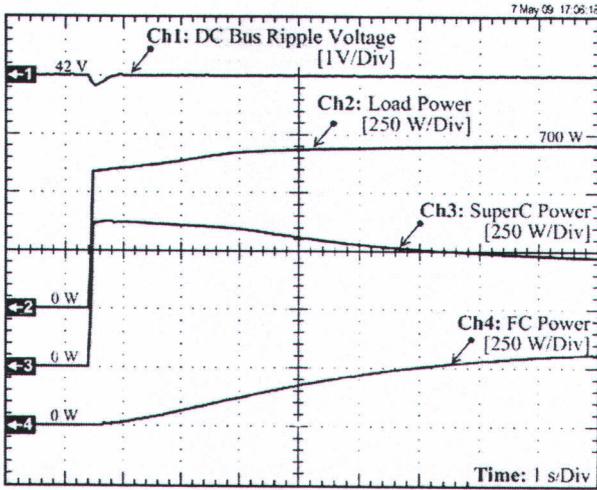


Fig. 8. Dynamic characteristic of the hybrid source during a step load from 0 to 700 W.

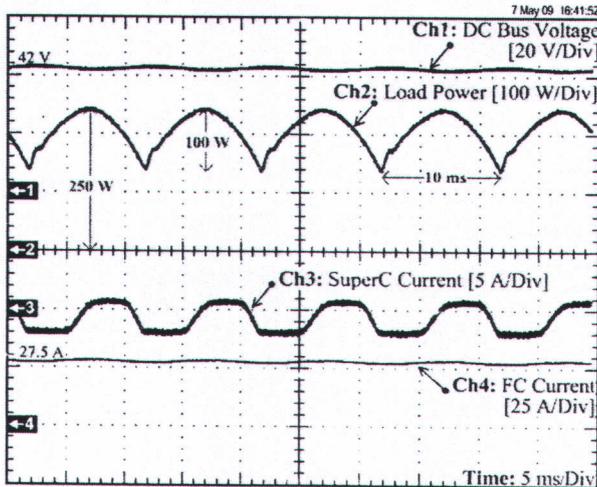


Fig. 9. Hybrid source response during load power with a low frequency of 100 Hz.

load power demanded (disturbance). It shows the dc-bus ripple voltage (state variable  $x_1$ ), the load power, the supercapacitor power, and the FC power. Once again, the supercapacitor supplies most of the power that is required during the high step load. The experimental results reveal only small perturbations on the dc-bus voltage waveform, which is of major importance by using the flatness-based control law for the dc-bus energy regulation in the proposed system.

To present the hybrid power-source response to the load power with a low frequency power demanded, the oscilloscope waveforms in Fig. 9 show the dc-bus voltage (state variable  $x_1$ ), the load power, the supercapacitor current, and the FC current. This test functions to observe the control law performance when the dc bus is connected with a single-phase inverter at 50 Hz. As a result, the load power frequency at the dc bus is 100 Hz. One can see that the supercapacitor supplies most of the low frequency for the load power. The experimental results reveal the regulation of the dc-bus voltage waveform, and the FC power is nearly constant for the average load power, which is

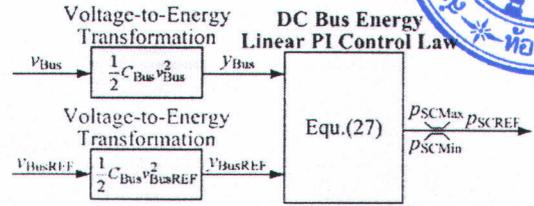


Fig. 10. DC link stabilized FC/supercapacitor hybrid source based on linear PI control law.

of major importance by using the flatness-based control law for the dc-bus energy regulation in the proposed system.

#### D. Performance Comparison Between the Flatness Control and the Classical Linear PI Control

To compare the performance of the flatness-based control, a traditional linear proportional–integral (PI) control method presented in [17] is also detailed. Here, we briefly review this approach. A desired reference for the dc-bus energy is represented by  $y_{BUSREF}$  ( $y_{1REF}$ ). A linear feedback PI control law is given by the following expression:

$$p_{SCREF} = K_P (y_{BUSREF} - y_{BUS}) + K_I \int_0^t (y_{BUSREF} - y_{BUS}) d\tau \quad (27)$$

where  $K_P$  and  $K_I$  are the set of controller parameters.

Therefore, because the supercapacitor current loop is much faster than the dc link voltage loop [so that it can be considered as a pure unity gain; see (6)], the open-loop transfer function associated with the dc link voltage regulation can be written as

$$\frac{y_{BUS}(s)}{y_{BUSREF}(s)} = \underbrace{\left( K_P + \frac{K_I}{s} \right)}_{\text{PI-Controller}} \cdot \underbrace{\frac{y_{BUS}/p_{SC}}{s}}_{\text{PI-Controller}} \cdot \underbrace{\frac{p_{SC}/p_{SCREF}}{T_P s + 1}}_{\text{PI-Controller}} \quad (28)$$

where  $T_P$  is the time constant of an equivalent first-order delay of the supercapacitor power regulation loop (or the supercapacitor current regulation loop). Thus, the linear control law of the dc link stabilization previously detailed is portrayed in Fig. 10. It is similar to the nonlinear control law (see Fig. 4), where the PI controller also generates a supercapacitor power reference  $p_{SCREF}$ .

To compare the performance of the flatness-based control and the linear PI control laws, the simulation was implemented. Simulations with MATLAB/Simulink were performed using a reduced-order model of the power plant, as portrayed in Fig. 1. To give a reasonable comparison between the methods, the parameters of the linear PI controller  $K_P$  and  $K_I$  were tuned to obtain the best possible performance, and this result is compared with the flatness-based control. Then,  $K_P = 600 \text{ W} \cdot \text{J}^{-1}$ , and  $K_I = 100\,000 \text{ W} \cdot (\text{J} \cdot \text{s})^{-1}$ ; therefore, the desired phase margin  $PM$  is equal to  $60^\circ$ . If  $K_P = 720 \text{ W} \cdot \text{J}^{-1}$  and  $K_I = 200\,000 \text{ W} \cdot (\text{J} \cdot \text{s})^{-1}$ , then the desired phase margin  $PM$  is equal to  $50^\circ$ .

Fig. 11 shows simulation results obtained for both controllers during the large load step. It is similar to the test bench results illustrated in Fig. 8. The flatness-based control

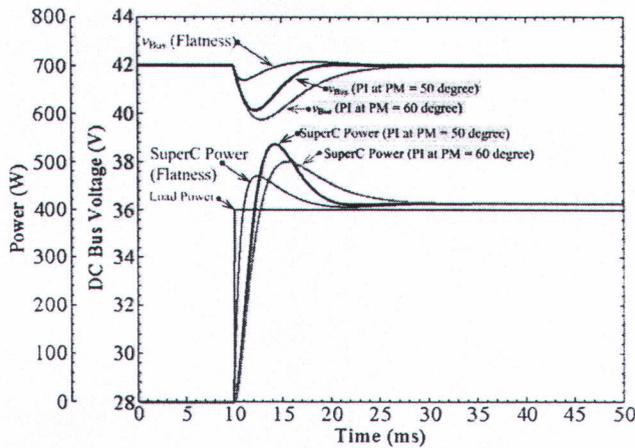


Fig. 11. Simulation results. Comparison of the flatness-based control law with a linear PI control law. Response to a large load step from 0 to 400 W at  $t = 10$  ms.

shows good convergence of the dc-bus voltage regulation to its desired reference of 42 V. Although the dynamic response of the linear control law could be improved (by reducing the phase margin  $PM$ ) relative to that shown in the figures, this enhancement came at the expense of a reduced stability margin (see Fig. 11). From these results, we conclude that the flatness-based control provides better performance than the classical PI controller.

V. CONCLUSION

There is an essential need for an efficient ES system that is affordable and has a drive cycle life for future FC vehicles. This paper has focused on the dynamic performance by taking account of the intrinsic energetic characteristics of these sources (i.e., energy and power densities and typical operating dynamics) in the energy-management strategy. Hence, the control approach, based on the differential flatness control, presents the robustness, stability, and efficiency of the FC/supercapacitor hybrid power source. The control laws illustrate how to circumvent the fast transition of the FC power and then reducing the FC stack stress. As a result, the hybrid source lifetime is theoretically increased.

To ensure the energy-efficient operation of the FC stack, the output current ripple of the FC stack is minimized by parallel boost converters with interleaving switching technique for a high-frequency ripple (25-kHz pulse width modulation) by the supercapacitor for a low-frequency ripple (e.g., 100 for single systems).

Experimental results in the laboratory carried out using a small-scale test bench, which employs a PEMFC (500 W, 50 A), and a storage device of supercapacitor bank (292 F, 30 V) corroborate the excellent performances during load cycles.

APPENDIX

This Appendix gives a brief theory of the differential flatness [26], [39]. A system of ordinary differential equations (A-1) is

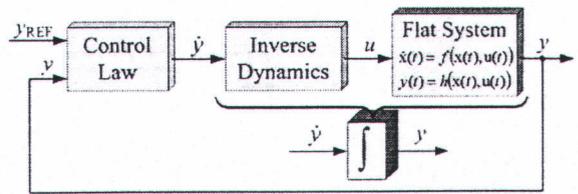


Fig. 12. Concept of flatness-based control, where  $y$  is the output variable,  $y_{REF}$  is the output set point, and  $u$  is the control input variable.

said to be differentially flat, if there exist variables (denoted by the flat outputs  $y$ ) such that

$$\dot{x} = f(x, u) \tag{A-1}$$

$$x = [x_1, x_2, \dots, x_n]^T \quad x \in \mathbb{R}^n \tag{A-2}$$

$$u = [u_1, u_2, \dots, u_m]^T \quad u \in \mathbb{R}^m \tag{A-3}$$

$$y = [y_1, y_2, \dots, y_m]^T \quad y \in \mathbb{R}^m \tag{A-4}$$

where  $x$  is the state variable,  $u$  is the vector of input (control) variables, and  $(n, m) \in \mathbb{N}$ .

- 1) These variables are functions of the states, inputs, and finite derivatives of the inputs of the form

$$y = \phi(x, u, \dot{u}, \dots, u^{(\alpha)}) \tag{A-5}$$

where  $\alpha$  is the finite number of derivatives.

- 2) All the states and inputs can be expressed in terms of flat outputs and their derivatives by equations of the type

$$x = \varphi(y, \dot{y}, \dots, y^{(\beta)}) \tag{A-6}$$

$$u = \psi(y, \dot{y}, \dots, y^{(\beta+1)}) \tag{A-7}$$

where  $\beta$  is the finite number of derivatives.

- 3) There is no differential equation of the form

$$0 = \zeta(y, \dot{y}, \dots, y^{(\delta)}) \tag{A-8}$$

where  $\delta$  is the finite number of derivative.

Note that the vector function  $f$  in (A-1) is assumed to be smooth. As depicted in Fig. 12, nonlinear flat systems are equivalent to linear controllable systems. The flat outputs  $y$  and their derivatives provide an alternate representation of the system dynamics such that if the flat output's profiles are known as a function of time, then one can obtain the profiles of all the system states and the corresponding inputs. This property is used to calculate the flat output's trajectories, which are then mapped to the inputs  $u$ . Clearly, the advantages of the differential flatness approach is that the trajectories of the system, i.e.,  $(x, u)$ , are straightforwardly estimated by the trajectories of  $y$  and their derivatives without integrating any differential equation [40].

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## REFERENCES

- [1] B. Blunier, M. Pucci, G. Cirrincione, M. Cirrincione, and A. Miraoui, "A scroll compressor with a high-performance sensorless induction motor drive for the air management of a PEMFC system for automotive applications," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3413–3427, Nov. 2008.
- [2] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat, and M. Hinajc, "Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3892–3904, Oct. 2009.
- [3] N. Yousfi-Steiner, P. Moçotéguy, D. Candusso, and D. Hissel, "A review on polymer electrolyte membrane fuel cell catalyst degradation and starvation issues: Causes, consequences and diagnostic for mitigation," *J. Power Sources*, vol. 194, no. 1, pp. 130–145, Oct. 2009.
- [4] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel starvation: Analysis of a PEM fuel cell system," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 52–59, Jul./Aug. 2009.
- [5] D. Feroldi, M. Serra, and J. Riera, "Design and analysis of fuel-cell hybrid systems oriented to automotive applications," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 4720–4729, Nov. 2009.
- [6] J. Bernard, S. Delprat, F. N. Büchi, and T. M. Guerra, "Fuel-cell hybrid powertrain: Toward minimization of hydrogen consumption," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3168–3176, Sep. 2009.
- [7] A. Bergen, L. Pitt, A. Rowe, P. Wild, and N. Djilali, "Experimental assessment of a residential scale renewable-regenerative energy system," *J. Power Sources*, vol. 186, no. 1, pp. 158–166, Jan. 2009.
- [8] P. Corbo, F. Migliardini, and O. Veneri, "An experimental study of a PEM fuel cell power train for urban bus application," *J. Power Sources*, vol. 181, no. 2, pp. 363–370, Jul. 2008.
- [9] A. E. Auld, J. Brouwer, K. M. Smedley, and S. Samuelsen, "Load-following strategies for evolution of solid oxide fuel cells into model citizens of the grid," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 617–625, Sep. 2009.
- [10] J. Bauman and M. Kazerani, "A comparative study of fuel-cell–battery, fuel-cell–ultracapacitor, and fuel-cell–battery–ultracapacitor," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 760–769, Mar. 2008.
- [11] P. Thounthong, S. Raël, and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," *J. Power Sources*, vol. 193, no. 1, pp. 376–385, Aug. 2009.
- [12] J. Bauman and M. Kazerani, "An analytical optimization method for improved fuel cell–battery–ultracapacitor powertrain," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3186–3197, Sep. 2009.
- [13] E. Schaltz, A. Khaligh, and P. O. Rasmussen, "Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3882–3891, Oct. 2009.
- [14] D. Feroldi, M. Serra, and J. Riera, "Energy management strategies based on efficiency map for fuel cell hybrid vehicles," *J. Power Sources*, vol. 190, no. 2, pp. 387–401, May 2009.
- [15] S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura, "Integration of an energy capacitor system with a variable-speed wind generator," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 740–749, Sep. 2009.
- [16] M. Uzunoglu and M. S. Alam, "Modeling and analysis of an FC/UC hybrid vehicular power system using a novel-wavelet-based load sharing algorithm," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 263–272, Mar. 2008.
- [17] P. Thounthong, S. Raël, and B. Davat, "Analysis of supercapacitor as second source based on fuel cell power generation," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 247–255, Mar. 2009.
- [18] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 148–155, Jan. 2008.
- [19] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721–2735, Sep. 2008.
- [20] S. Y. Choe, J. W. Ahn, J. G. Lee, and S. H. Baek, "Dynamic simulator for a PEM fuel cell system with a PWM DC/DC converter," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 669–680, Jun. 2008.
- [21] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel cell high-power applications," *IEEE Ind. Electron. Mag.*, vol. 3, no. 1, pp. 32–46, Mar. 2009.
- [22] K. Rajashekar, J. Grieve, and D. Daggett, "Hybrid fuel cell power in aircraft," *IEEE Ind. Appl. Mag.*, vol. 14, no. 4, pp. 54–60, Jul./Aug. 2008.
- [23] A. Payman, S. Pierfederici, and F. Meibody-Tabar, "Energy control of supercapacitor/fuel cell hybrid power source," *Energy Convers. Manage.*, vol. 49, no. 6, pp. 1637–1644, Jun. 2008.
- [24] S. Jain and V. Agarwal, "An integrated hybrid power supply for distributed generation applications fed by nonconventional energy sources," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 622–631, Jun. 2008.
- [25] S. Teleke, M. E. Baran, A. Q. Huang, S. Bhattacharya, and L. Anderson, "Control strategies for battery energy storage for wind farm dispatching," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 725–732, Sep. 2009.
- [26] M. Fliess, J. Lévine, P. Martin, and P. Rouchon, "Flatness and defect of nonlinear systems: Introductory theory and examples," *Int. J. Control*, vol. 61, no. 6, pp. 1327–1361, Jun. 1995.
- [27] M. Guay, "On the linearizability of nonisothermal continuous stirred-tank reactors," *Automatica*, vol. 38, no. 2, pp. 269–278, Feb. 2002.
- [28] J. Villagra, B. A. Novel, H. Mounier, and M. Pengov, "Flatness-based vehicle steering control strategy with SDR feedback gains tuned via a sensitivity approach," *IEEE Trans. Control Syst. Technol.*, vol. 15, no. 3, pp. 554–564, May 2007.
- [29] H. Aschemann and D. Schindele, "Sliding-mode control of a high-speed linear axis driven by pneumatic muscle actuators," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 3855–3864, Nov. 2008.
- [30] M. A. Danzer, J. Wilhelm, H. Aschemann, and E. P. Hofer, "Model-based control of cathode pressure and oxygen excess ratio of a PEM fuel cell system," *J. Power Sources*, vol. 176, no. 2, pp. 515–522, Feb. 2008.
- [31] P. S. P. da Silva and P. Rouchon, "Flatness-based control of a single qubit gate," *IEEE Trans. Autom. Control*, vol. 53, no. 3, pp. 775–779, Apr. 2008.
- [32] E. Song, A. F. Lynch, and V. Dinavahi, "Experimental validation of nonlinear control for a voltage source converter," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 5, pp. 1135–1144, Sep. 2009.
- [33] T. Rabbani, S. Munier, D. Dorchie, P. Malaterre, A. Bayen, and X. Litrico, "Flatness-based control of open-channel flow in an irrigation canal using scada," *IEEE Control Syst. Mag.*, vol. 29, no. 5, pp. 22–30, Oct. 2009.
- [34] A. Gensior, H. Sira-Ramirez, J. Rudolph, and H. Guldner, "On some nonlinear current controllers for three-phase boost rectifiers," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 360–370, Feb. 2009.
- [35] V. Morio, F. Cazaurang, and P. Vernis, "Flatness-based hypersonic reentry guidance of a lifting-body vehicle," *Control Eng. Pract.*, vol. 17, no. 5, pp. 588–596, May 2009.
- [36] S. K. Agrawal, K. Pathak, J. Franch, R. Lampariello, and G. Hirzinger, "A differentially flat open-chain space robot with arbitrarily oriented joint axes and two momentum wheels at the base," *IEEE Trans. Autom. Control*, vol. 54, no. 9, pp. 2185–2191, Sep. 2009.
- [37] W.-K. Na and B. Gou, "Feedback-linearization-based nonlinear control for PEM fuel cells," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 179–190, Mar. 2008.
- [38] C. P. Mudannayake and M. F. Rahman, "Control design for an induction machine based 42 V integrated starter alternator," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 14–25, Jul./Aug. 2009.
- [39] M. Fliess, J. Lévine, P. Martin, and P. Rouchon, "A lie–backlund approach to equivalence and flatness of nonlinear systems," *IEEE Trans. Autom. Control*, vol. 44, no. 5, pp. 922–937, May 1999.
- [40] G. Millérioux and J. Daafouz, "Flatness of switched linear discrete-time systems," *IEEE Trans. Autom. Control*, vol. 54, no. 3, pp. 615–619, Mar. 2009.



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Photographs and biographies for the last four authors not available at the time of publication.



# Analysis of Differential Flatness-Based Control for a Fuel Cell Hybrid Power Source

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**Abstract**—This paper presents an innovative control law for distributed dc generation supplied by a fuel cell (FC) (main source) and supercapacitor (auxiliary source). This kind of system is a multiconverter structure and exhibits nonlinear behavior. The operation of a multiconverter structure can lead to interactions between the controls of the converters if they are designed separately. Typically, interactions between converters are studied using impedance criteria to investigate the stability of cascaded systems. In this paper, a nonlinear control algorithm based on the flatness properties of the system is proposed. Flatness provides a convenient framework for meeting a number of performance specifications for the hybrid power source. Using the flatness property, we propose simple solutions to hybrid energy management and stabilization problems. The design controller parameters are autonomous of the operating point; moreover, interactions between converters are taken into account by the controllers, and high dynamics in disturbance rejection is achieved. To validate the proposed method, a hardware system is realized with analog circuits, and digital estimation is accomplished with a dSPACE controller. Experimental results with small-scale devices (a polymer electrolyte membrane FC of 1290 W, 46 A and a supercapacitor module of 100 F, 500 A, and 32 V) in a laboratory corroborate the excellent control scheme during a motor-drive cycle.

**Index Terms**—Converters, current control, electric vehicles, energy management, flatness-based control, fuel cells (FCs), supercapacitor.

## I. INTRODUCTION

RENEWABLE energy sources [such as wind turbines, photovoltaics, and fuel cells (FCs)] are expected to provide a higher proportion of the world's energy demand in the near future. FCs, in particular, are anticipated to play a significant role

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in helping to meet the demands of power quality and reliability of distributed power generation [1], [2].

It is believed that FC vehicles could revolutionize the automobile industry by replacing internal combustion engine (ICE) technology [3]. As reported in [4], for vehicle applications, the total efficiency of an ICE based on a propulsion system and FC vehicle comprises the well-to-tank efficiency and the tank-to-wheel efficiency. Overall, the FC vehicle is more efficient than the ICE vehicle. The well-to-wheel efficiencies are 21.7 and 13.8% for FC and ICE vehicles, respectively. For hydrogen manufacture, there are many ways to produce hydrogen, particular from wind turbines and photovoltaic cells [5].

According to recent works on FC characteristics [6]–[9], the specific properties of FCs that result in a delayed output power response are related to processing time through subsidiary equipments, and slow internal electrochemical and thermodynamic characteristics. Therefore, in order to supply electric power to fluctuating loads via the hybrid system of the FC, an electric energy storage system is needed to compensate the gap between the output from the FC and the load, in addition to collaborative load sharing. At the moment, based on present storage device technology, the supercapacitor (or “ultracapacitor”) storage device has received wide attention [10], [11] as an auxiliary power source.

The primary difference between batteries and supercapacitors is that the former store energy in the bulk of chemical reactants capable of generating charge, whereas the latter store energy directly as surface charge. Battery discharge rate and, therefore, power performance is limited by reaction kinetics as well as mass transport, while such limitations do not apply to supercapacitors constructed with two activated carbon electrodes, thereby allowing exceptionally high power capability during both charge and discharge [12]. In addition, the highly reversible electrostatic charge storage mechanism in supercapacitors does not lead to the volume changes observed in batteries with electrochemical transformations of active masses. This volume change limits the lifetime cycle of batteries usually to several hundred cycles, whereas supercapacitors have demonstrated from hundreds of thousands to many millions of full-charge/discharge cycles [10].

Previous research works have shown that hybridization of FC vehicles with batteries [13], [14], supercapacitors (ultracapacitors) [15], [16], and battery/supercapacitors [17], [18], provides cost, performance, and operational improvements, as well as fuel economy benefits that are attractive and should be considered. As reported in [19], an FC/supercapacitor hybrid source has better performance than an FC/battery source, because the supercapacitor can more effectively assist the FC

83 to meet the transient power demand, and high-current charges  
84 and discharges from batteries will also have a reduced lifetime.  
85 Even better, hybrid source in a FC/battery/supercapacitor com-  
86 bination has been presented in [18]. A main improvement of the  
87 FC/battery/supercapacitor vehicle is the increase in the battery  
88 lifetime due to reduction of high-current charges and discharges.

89 However, there are still some aspects of control methods  
90 to be studied, particularly in the area of dynamics, robust-  
91 ness, stability, and efficiency. Recent work on controlling a  
92 FC/supercapacitor hybrid power plant is reported in [16], where  
93 a linear control using PI compensator was proposed for dc-  
94 link stabilization. Design controller parameters based on linear  
95 methods require a linear approximation, where this is dependent  
96 on the operating point. Because the switching model of the hy-  
97 brid power plant is nonlinear, it is natural to apply model-based  
98 nonlinear control strategies that directly compensate for system  
99 nonlinearity without requiring a linear approximation [20].

100 Differential flatness theory (nonlinear approach) was first in-  
101 troduced by Fliess *et al.* [21]. This allowed an alternate repre-  
102 sentation of the system, where trajectory planning and nonlinear  
103 controller design is clear-cut. These ideas have been used lately  
104 in a variety of nonlinear systems across various engineering  
105 disciplines including: control of a high-speed linear axis driven  
106 by pneumatic muscle actuators [22], control of cathode pressure  
107 and oxygen excess ratio of a proton exchange membrane (PEM)  
108 fuel cell system [23], steering control of a two-level quantum  
109 system [24], reactive power and dc voltage tracking control of  
110 a three-phase voltage source converter [25], control of open-  
111 channel flow in an irrigation canal [26], current control for three  
112 phase three-wire boost converters [27], design of a guidance al-  
113 gorithm for the hypersonic phase of a lifting-body vehicle [28],  
114 and control of a space robot with arbitrarily oriented joint axes  
115 and two momentum wheels at the base [29].

116 In this paper, we present an innovative control approach called  
117 differential flatness to manage energy in the proposed system.  
118 This paper is focused on a special control strategy and control  
119 law. This method enables the management of transient power  
120 demand, power peaks, and regenerative braking, particularly in  
121 future FC vehicle applications, in light of FC and supercapacitor  
122 constraints. It will provide a new contribution to the field of the  
123 multisource system. The general structure of the studied system,  
124 the new control algorithm of the hybrid source, realization of the  
125 experimental bench, and experimental validation are presented  
126 in the following sections.

## 127 II. FC HYBRID POWER SOURCE

### 128 A. Proposed Hybrid Structure

129 Low-voltage, high-current (power) converters are needed  
130 because of the electrical characteristics of FCs and superca-  
131 pacitors. A classical boost converter is often used as an FC con-  
132 verter [30], [31], and a classical two-quadrant (bidirectional)  
133 converter is often used as a supercapacitor or battery con-  
134 verter [32]. However, the classical converters will be limited  
135 when the power increases or at higher step-up ratios. As such,  
136 the use of parallel power converters (multiphase converters in  
137 parallel) with interleaving may offer better performance [33].

138 In the interleaving method, the converter modules all operate  
139 at the same switching frequency. Their switching waveforms are  
140 displaced in phase with respect to one another by  $2\pi/N$  radians  
141 over the switching period, with  $N$  being the number of converters  
142 working in parallel. The interleaved converter can benefit both  
143 high current and high power density designs. It is ideal for dc-  
144 bus converters and merchant power applications because the  
145 reduced input ripple current and reduced output capacitor ripple  
146 current lessen the electrical stress on the dc capacitors [33].

147 Fig. 1 depicts the proposed hybrid source structure. The FC  
148 converter combines four-phase parallel boost converters with  
149 interleaving, and the supercapacitor converter employs four-  
150 phase parallel bidirectional converters with interleaving. These  
151 latter two converters are in the high-current and low-voltage  
152 sections. In order to obtain a higher utility voltage level, a three-  
153 level boost converter can be used as a high-voltage section.  
154 The use of a high-voltage section converter leads to better ef-  
155 ficiency of the global conversion structure due to the use of  
156 MOSFET/Schottky diode technology rather than insulated gate  
157 bipolar transistor (IGBT)/ultrafast diode technology [34].

158 Constraints in operating the three-level boost converter are  
159 to regulate the input current  $i_{Load}$ , the dc-bus output  $v_{Out}$  and  
160 to ensure the balance of voltages across capacitors  $C_1$  and  $C_2$ .  
161 It is beyond the scope of this paper to present the three-level  
162 boost converter. For more details may be found in [34]. Thus,  
163 the following presentation will detail only with the low-voltage  
164 and high-current section.

165 For safety and high dynamics, the FC and supercapacitor  
166 converters are typically controlled primarily by inner current  
167 regulation loops. The current controls of these converters, as  
168 illustrated in Fig. 2, are similar to the basic current control  
169 of parallel converters. These controls can be easily realized  
170 with linear (PI) or nonlinear (sliding mode) current controllers  
171 [35]. The dynamics of the current regulation loops are also  
172 supposed to be much faster than those of the outer control loops  
173 [36]. These current control loops are supplied by two reference  
174 signals: the supercapacitor current reference  $i_{SCREF}$  and the FC  
175 current reference  $i_{FCREF}$  generated by the energy management  
176 algorithm presented hereafter.

### 177 B. Reduced-Order Model of FC/Supercapacitor Converters

178 We suppose that the FC and supercapacitor currents follow  
179 their reference values completely. Thus,

$$180 \quad i_{FC} = i_{FCREF} = \frac{p_{FC}}{v_{FC}} = \frac{p_{FCREF}}{v_{FC}} \quad (1)$$

$$181 \quad i_{SC} = i_{SCREF} = \frac{p_{SC}}{v_{SC}} = \frac{p_{SCREF}}{v_{SC}} \quad (2)$$

182 A reduced-order model [37] of the studied power converters  
183 is shown in Fig. 3. Now, the FC generator and the supercapacitor  
184 storage device function as controlled current sources. We con-  
185 sider here that there are only static losses in these converters, and  
186  $r_{FC}$  and  $r_{SC}$  represent static losses in the FC and supercapacitor  
187 converters, respectively.

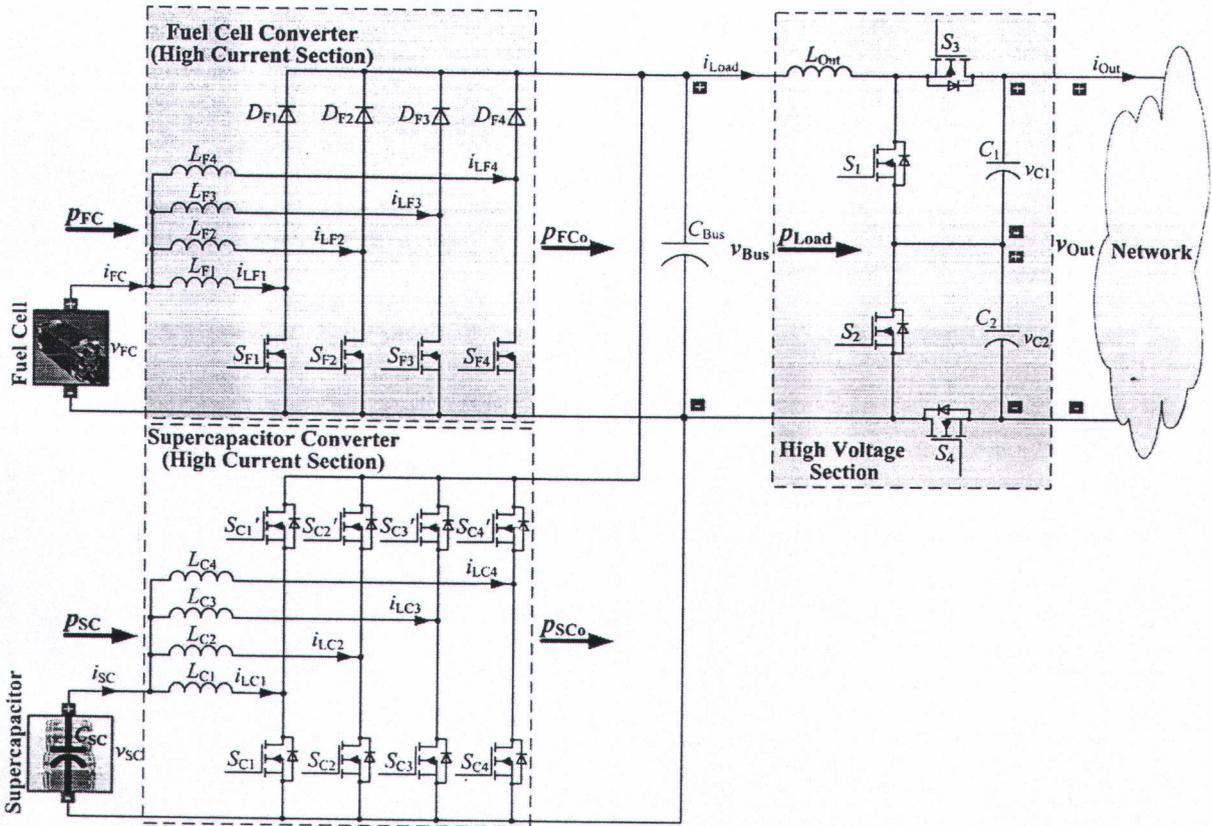


Fig. 1. Proposed distributed generation system supplied by fuel cell and supercapacitor, where  $p_{Load} (= v_{Bus} \cdot i_{Load})$ ,  $v_{Bus}$ , and  $i_{Load}$  are the load power, the dc-bus voltage, and the dc-bus load current, respectively.  $p_{FC} (= v_{FC} \cdot i_{FC})$ ,  $v_{FC}$ , and  $i_{FC}$  are the FC power, voltage, and current, respectively.  $p_{SC} (= v_{SC} \cdot i_{SC})$ ,  $v_{SC}$ , and  $i_{SC}$  are the supercapacitor power, voltage, and current, respectively.  $p_{FC0}$  and  $p_{SC0}$  are the output powers to the dc link from the converters of FC and supercapacitor, respectively.

186 The dc-bus capacitive energy  $y_{Bus}$ , and the supercapacitive  
187 energy  $y_{SC}$  can be written as follows:

$$y_{Bus} = \frac{1}{2} C_{Bus} v_{Bus}^2 \quad (3)$$

$$y_{SC} = \frac{1}{2} C_{SC} v_{SC}^2. \quad (4)$$

188 The total electrostatic energy  $y_T$  stored in the dc-bus capacitor  
189  $C_{Bus}$  and the supercapacitor  $C_{SC}$  can also be written as follows:

$$y_T = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2. \quad (5)$$

190 The dc-bus capacitive energy  $y_{Bus}$  is given versus  $p_{FC0}$ ,  $p_{SC0}$ ,  
191 and  $p_{Load}$  by the following differential equation:

$$\dot{y}_{Bus} = p_{FC0} + p_{SC0} - p_{Load} \quad (6)$$

192 where

$$p_{FC0} = p_{FC} - r_{FC} \left( \frac{p_{FC}}{v_{FC}} \right)^2 \quad (7)$$

$$p_{SC0} = p_{SC} - r_{SC} \left( \frac{p_{SC}}{v_{SC}} \right)^2 \quad (8)$$

$$p_{Load} = v_{Bus} i_{Load} = \sqrt{\frac{2y_{Bus}}{C_{Bus}}} i_{Load} \quad (9)$$

$$p_{SC} = v_{SC} i_{SC} = \sqrt{\frac{2y_{SC}}{C_{SC}}} i_{SC}. \quad (10)$$

### III. CONTROL OF A HYBRID POWER SOURCE

194

#### A. Literature Review: Control of a Hybrid Power Source

195

The energy management of multipower sources has been  
studied recently: for example, by Feroldi *et al.* [38], who studied  
the control (based on the efficiency map) of a FC/supercapacitor  
hybrid power source for vehicle applications; by Jiang *et al.* [39],  
who studied the control (based on adaptive control with state-  
machine estimation) of a FC/battery hybrid power source; by  
Li and Liu [40], who studied the control (using a fuzzy power  
control algorithm) of a FC/battery hybrid power source; and  
by Thounthong *et al.*, whose work concerned a regulated dc-bus  
voltage FC/supercapacitor hybrid source (based on a basic linear  
controller operated by setting controller parameters that depend  
on a defined operating point) [16], a regulated dc-bus voltage  
FC/battery/supercapacitor hybrid source (based on a basic linear  
controller operated by setting controller parameters that depend  
on a defined operating point) [18] and an unregulated dc-bus  
voltage FC/battery hybrid source (based on the battery state-  
of-charge) [14]. Nevertheless, in these structures, there are still  
some aspects about the control laws that remain open to study,

213

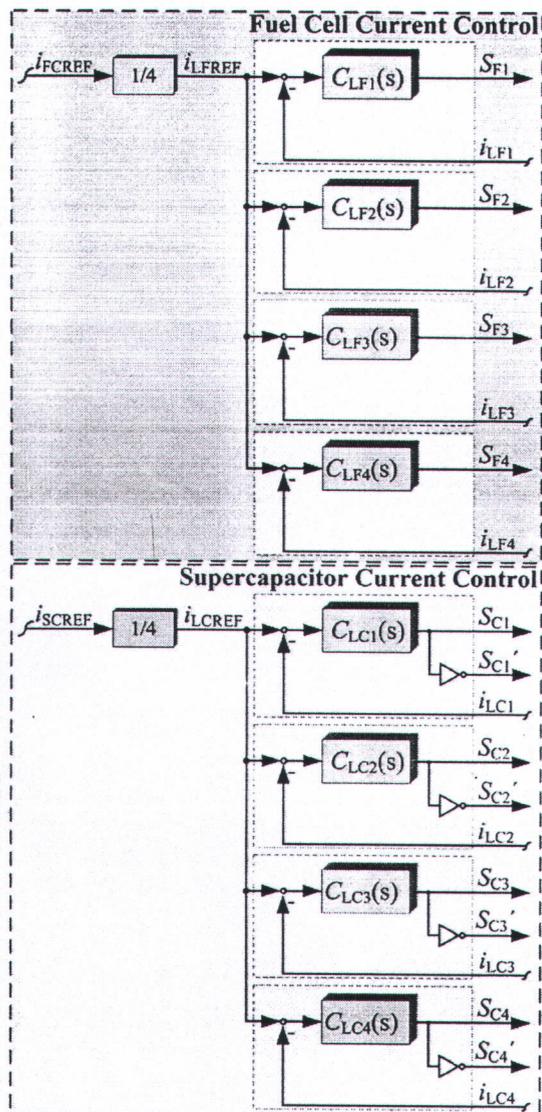


Fig. 2. Current control loops of the proposed FC/supercapacitor converters.

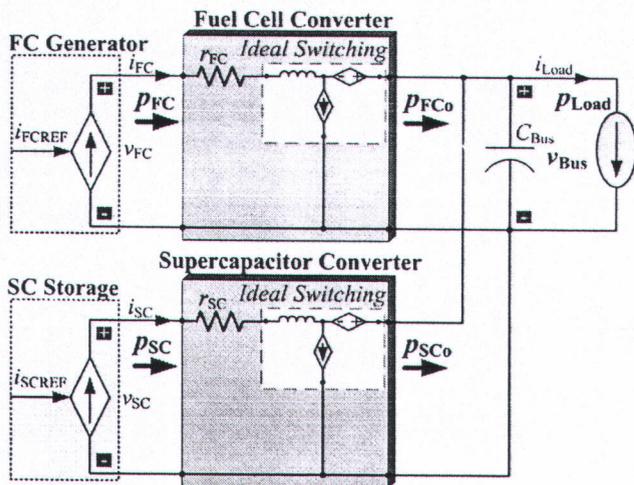


Fig. 3. Reduced-order model of the studied power converters.

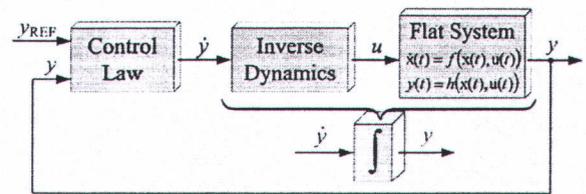


Fig. 4. Concept of control system based on the flatness principle, where  $y$  is the output variable,  $y_{REF}$  is the output set point, and  $u$  is the control input variable.

particularly in the area of dynamics, robustness, stability, and efficiency. 214 215

### B. Brief Theory of Differential Flatness 216

The theory of differential flatness consists of a parameteriza- 217  
tion of the trajectories of a system by one of its outputs  $y$ , called 218  
the *flat output*, and its derivatives. Here, we consider general 219  
nonlinear systems of the form 220

$$\dot{x} = f(x, u) \quad (11)$$

$$x = [x_1, x_2, \dots, x_n]^T, x \in \mathbb{R}^n \quad (12)$$

$$u = [u_1, u_2, \dots, u_m]^T, u \in \mathbb{R}^m \quad (13)$$

where  $x$  is the state variable,  $u$  is the vector of input (control) 221  
variables, and  $(n, m) \in \mathbb{N}$ . 222

According to Fliess *et al.* [21], [41], if the state variable  $x$  can 223  
be parameterized by output  $y$  and its derivatives, an autonomous 224  
dynamical system, (i.e., (11) with time removed) is said to be 225  
differentially flat and admits the flat output  $y$  226

$$y = [y_1, y_2, \dots, y_m]^T; y \in \mathbb{R}^m \quad (14)$$

with 227

$$y = \phi(x, u, \dot{u}, \dots, u^{(\alpha)}) \quad (15)$$

such that the state variable and control variable can be written 228  
as follows: 229

$$x = \varphi(y, \dot{y}, \dots, y^{(\beta)}) \quad (16)$$

$$u = \psi(y, \dot{y}, \dots, y^{(\beta+1)}) \quad (17)$$

where  $\alpha$  and  $\beta$  are the finite numbers of derivative. As depicted 230  
in Fig. 4, nonlinear flat systems are equivalent to linear controll- 231  
able systems. Therefore, a dynamical system is naturally 232  
differentially flat if it is equivalent to a system without dynam- 233  
ics, i.e., a static system [22], [23]. The aforementioned equations 234  
mean that there exists a quantity  $y$  that summarizes the behavior 235  
of the whole system via the mappings  $\varphi$  and  $\psi$ . Clearly, the 236  
advantage of the differential flatness approach is that the trajec- 237  
tories of the system, i.e.,  $(x, u)$  are straightforwardly estimated 238  
by the trajectories of  $y$  and its derivatives without integrating 239  
any differential equation [29], [42]. 240

### 241 C. Proposed Differential Flatness-Based Control Hybrid 242 Source

243 In the proposed system depicted in Fig. 1, there are two  
244 voltage variables or two energy variables to be regulated.

- 245 1) The dc-bus energy  $y_{Bus}$  is the most important variable.
- 246 2) The supercapacitor storage energy  $y_{SC}$  is of secondary  
247 importance.

248 Therefore, based on the previous literature referenced earlier,  
249 we propose to utilize the supercapacitors, the fastest energy  
250 source of the proposed system, to supply the energy for the dc  
251 bus [16], [18]. Hence, the FC (as the slowest dynamic device)  
252 functions to supply the energy to both the dc-bus capacitor  $C_{Bus}$   
253 and the supercapacitors  $C_{SC}$  to keep them charged.

254 The flat output  $\mathbf{y} = [y_1, y_2]^T$ , control variable  $\mathbf{u} = [u_1, u_2]^T$ ,  
255 and state variable  $\mathbf{x} = [x_1, x_2]^T$  are defined as follows:

$$\mathbf{y} = \begin{bmatrix} y_{Bus} \\ y_T \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} p_{SCREF} \\ p_{FCREF} \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} v_{Bus} \\ v_{SC} \end{bmatrix}. \quad (18)$$

256 From (3) and (5), the state variables  $\mathbf{x}$  can be written as  
257 follows:

$$x_1 = \sqrt{\frac{2y_1}{C_{Bus}}} = \varphi_1(y_1) \quad (19)$$

$$x_2 = \sqrt{\frac{2(y_2 - y_1)}{C_{SC}}} = \varphi_2(y_1, y_2). \quad (20)$$

258 From (6), the control variables  $\mathbf{u}$  can be calculated from the  
259 flat output  $\mathbf{y}$  and its time derivatives (*inverse dynamics*, see  
260 Fig. 4)

$$u_1 = 2p_{SCMax} \left[ 1 - \sqrt{1 - \left( \frac{\dot{y}_1 + \sqrt{(2y_1/C_{Bus})i_{Load} - p_{FCo}}}{p_{SCMax}} \right)^2} \right] \\ = \psi_1(y_1, \dot{y}_1) = p_{SCREF} \quad (21)$$

$$u_2 = 2p_{FCMax} \left[ 1 - \sqrt{1 - \left( \frac{\dot{y}_2 + \sqrt{(2y_1/C_{Bus})i_{Load}}}{p_{FCMax}} \right)^2} \right] \\ = \psi_2(y_1, \dot{y}_2) = p_{FCREF} \quad (22)$$

261 where

$$p_{SCMax} = \frac{v_{SC}^2}{4r_{SC}}, \quad p_{FCMax} = \frac{v_{FC}^2}{4r_{FC}}. \quad (23)$$

262 In this case,  $p_{SCMax}$  and  $p_{FCMax}$  are the limited maximum  
263 power of the supercapacitor and FC sources, respectively.

264 Thus, it is apparent that  $x_1 = \varphi_1(y_1)$ ,  $x_2 = \varphi_2(y_1, y_2)$ ,  
265  $u_1 = \psi_1(y_1, \dot{y}_1)$ , and  $u_2 = \psi_2(y_1, \dot{y}_2)$  correspond with (16)  
266 and (17). Consequently, the proposed reduced-order system can  
267 be considered as a flat system.

### 268 D. Control Law and Stability

269 For dc-bus energy regulation, a desired reference trajectory  
270 for the dc-bus energy is represented by  $y_{1REF}$ . A lineariz-  
271 ing feedback control law that performs exponential asymptotic

tracking of the trajectory is given by the following expres- 272  
sion [20], [27]: 273

$$(\dot{y}_1 - \dot{y}_{1REF}) + K_{11}(y_1 - y_{1REF}) + K_{12} \int (y_1 - y_{1REF}) d\tau = 0 \quad (24)$$

where the set of controller parameters  $(K_{11}, K_{12})$  is chosen, so 274  
that the roots of the closed-loop characteristic polynomial, in 275  
the complex variable  $s$ , is a *Hurwitz* polynomial 276

$$p(s) = s^2 + \lambda_1 s + \lambda_0. \quad (25)$$

Obviously, the tracking error  $e_1 = y_1 - y_{1REF}$  satisfies 277

$$\ddot{e}_1 + K_{11}\dot{e}_1 + K_{12}e_1 = 0. \quad (26)$$

The optimum choice of the design controller parameters 278  
is obtained by matching the characteristic polynomial  $p(s)$  279  
to a desired characteristic polynomial, with prespecified root 280  
locations. 281

We may set as the desired characteristic polynomial 282

$$p(s) = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (27)$$

$$K_{11} = 2\zeta\omega_n \quad (28)$$

$$K_{12} = \omega_n^2 \quad (29)$$

where  $\zeta$  and  $\omega_n$  are the desired dominant damping ratio and 283  
natural frequency. 284

It is noticeable that the control system is stable for  $K_{11}$ , 285  
 $K_{12} > 0$  ( $\zeta, \omega_n > 0$ ). However, based on the power electronic 286  
constant switching frequency  $\omega_S$  and cascade control structure, 287  
the outer control loop (here, the dc-bus energy control) must 288  
operate at a cutoff frequency  $\omega_E \ll \omega_C$  (the cutoff frequency 289  
of the supercapacitor power loop)  $\ll \omega_S$  [43]. Once the flat 290  
outputs are stabilized, the whole system is stable because all the 291  
variables of the system are expressed in terms of the flat outputs 292  
via (19)–(23). 293

The control law of the dc-bus energy loop detailed earlier is 294  
portrayed in Fig. 5. The dc-bus energy control law generates 295  
a supercapacitor power reference  $p_{SCREF}$ . This signal is then 296  
divided by the measured supercapacitor voltage  $v_{SC}$  and lim- 297  
ited to maintain the supercapacitor voltage within the interval 298  
[minimum  $V_{SCMin}$ , maximum  $V_{SCMax}$ ] by limiting the superca- 299  
pacitor charging current or discharging current, as presented in 300  
the block "superC current limitation function" [16]. This yields 301  
supercapacitor current reference  $i_{SCREF}$ . 302

For total energy regulation (or supercapacitor energy regu- 303  
lation), the desired reference trajectory for the total energy is 304  
represented by  $y_{2REF}$ . Because the supercapacitor has an enor- 305  
mous energy storage capacity, and because the supercapacitor 306  
energy is defined as a slower dynamic variable than the dc- 307  
bus energy variable, the total energy control law is defined as 308  
follows: 309

$$(\dot{y}_2 - \dot{y}_{2REF}) + K_{21}(y_2 - y_{2REF}) = 0. \quad (30)$$

Fig. 6 depicts the total energy control loop. The total energy 310  
control law generates the FC power reference  $p_{FCREF}$ . It must be 311  
restricted to an interval with maximum  $p_{FCMax}$  (corresponding 312  
to a rated power of the FC) and minimum  $p_{FCMin}$  (set to 0 W) 313

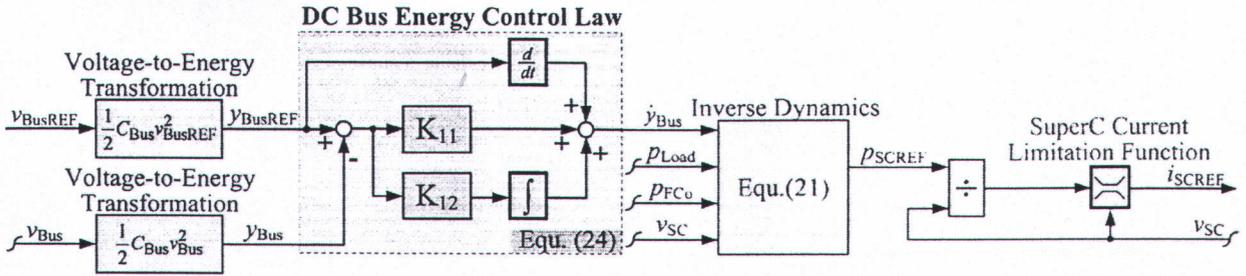


Fig. 5. Control law of the dc-bus energy regulation for FC/supercapacitor hybrid source.

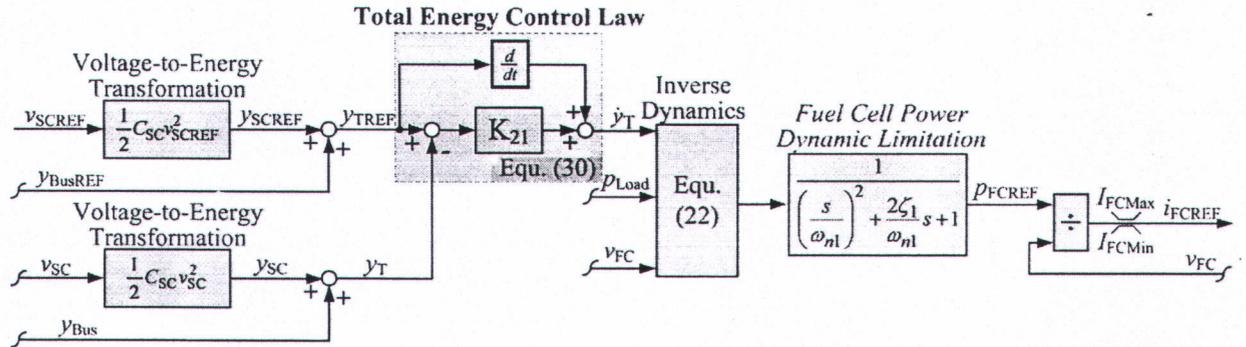


Fig. 6. Control law of the total energy regulation (charging supercapacitor) for FC/supercapacitor hybrid source.

314 as well as be limited in dynamics; these limitations ensure safe  
 315 operation of the FC with respect to the constraints that are  
 316 associated with the FC (i.e., the prevention of an FC stack from  
 317 undergoing fuel starvation [7]). Here, the second-order delay is  
 318 selected as the “fuel cell power dynamic limitation.”

319 The proposed control presents a solution of how to avoid fuel  
 320 starvation, which allows the FC system to operate at high effi-  
 321 ciency. In effect, the fuel flow varies depending on the power  
 322 demand, rather than being fixed to a constant fuel flow at a maxi-  
 323 mum value (the FC always has sufficient fuel flow). Nonetheless,  
 324 the operating system by fixing the fuel flow to a constant fuel  
 325 flow at a maximum value has low efficiency because fuel flow  
 326 (known as the power input of this generator) is always constant  
 327 at the maximum value [7].

#### 328 IV. EXPERIMENTAL VALIDATION

##### 329 A. Test Bench Description

330 In order to authenticate the proposed control algorithm and  
 331 control laws, a small-scale test bench of the hybrid system was  
 332 implemented in our laboratory, as presented in Fig. 7. The FC  
 333 system used in this effort was a PEMFC system (1.2 kW, 46 A;  
 334 Ballard Power Systems Company), as illustrated in Fig. 8. It was  
 335 supplied using pure hydrogen of regulated pressure at 10 bars  
 336 from bottles under a pressure of 150 bars and with clean and dry  
 337 air from a compressor. The supercapacitor module (100 F, 32 V;  
 338 Maxwell Technologies Company) was obtained by means of 12  
 339 BCAP1200 cells (capacitance: 1200 F and maximum voltage:  
 340 2.7 V) connected in series, as shown in Fig. 9.

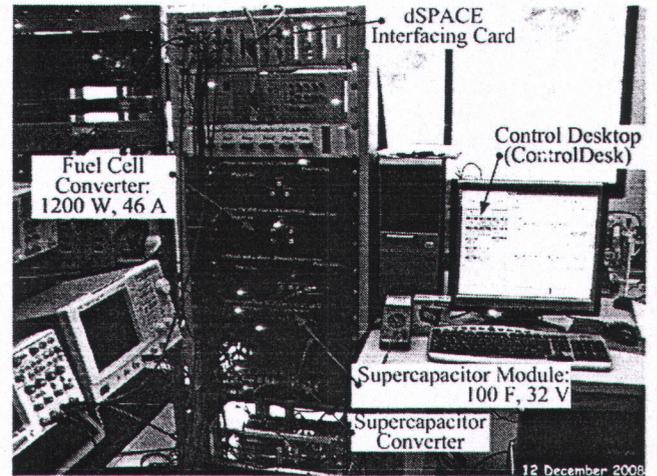


Fig. 7. Hybrid source test bench.

341 The FC converter (1.2 kW) and the supercapacitor converter  
 342 (4 kW) (see Fig. 1) were both realized in the laboratory. The con-  
 343 verter parameters and semiconductor components are detailed in  
 344 Table I.

##### 345 B. Control Description

346 Measurements of the FC current  $i_{FC}$ , the supercapacitor cur-  
 347 rent  $i_{SC}$ , the load current  $i_{Load}$ , the dc-bus voltage  $v_{Bus}$ , the FC  
 348 voltage  $v_{FC}$ , and the supercapacitor voltage  $v_{SC}$  were carried  
 349 out by means of zero-flux Hall effect sensors.

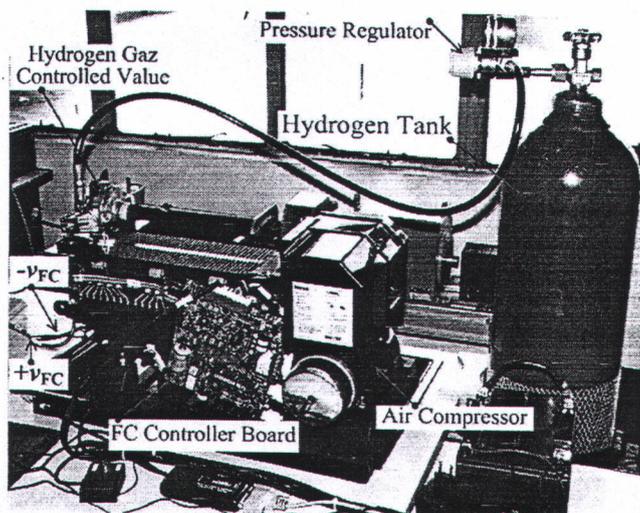


Fig. 8. Test bench of PEM fuel cell system of 1200 W, 46 A.

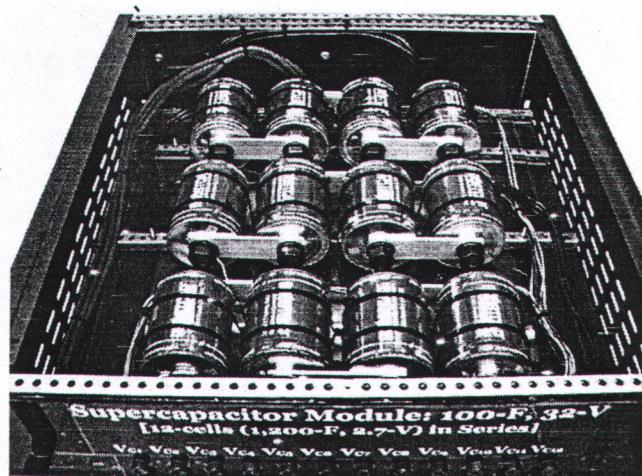


Fig. 9. Test bench of supercapacitor module of 100 F, 32 V.

 TABLE I  
 CONVERTER PARAMETERS AND SEMICONDUCTOR DEVICES

<b>Fuel Cell Converter:</b>		
Inductors $L_{F1}=L_{F2}=L_{F3}=L_{F4}$	396	$\mu\text{H}$
MOSFETs $S_{F1}=S_{F2}=S_{F3}=S_{F4}$	IRFP264N: 250 V, 38 A	
Diodes $D_{F1}=D_{F2}=D_{F3}=D_{F4}$	RURG3020: 200 V, 30 A	
<b>Supercapacitor Converter:</b>		
Inductors $L_{C1}=L_{C2}=L_{C3}=L_{C4}$	150	$\mu\text{H}$
MOSFETs $S_{C1}=S_{C2}=S_{C3}=S_{C4}$ $=S_{C1}'=S_{C2}'=S_{C3}'=S_{C4}'$	IRFP264N: 250 V, 38 A	

 TABLE II  
 DC-BUS ENERGY CONTROL LOOP PARAMETERS

$v_{\text{BusREF}}$	60	V
$C_{\text{Bus}}$	12,200	$\mu\text{F}$
$K_{11}$	141	$\text{rad}\cdot\text{s}^{-1}$
$K_{12}$	$10 \times 10^3$	$\text{rad}^2\cdot\text{s}^{-2}$
$r_{\text{FC}}$	0.10	$\Omega$
$r_{\text{SC}}$	0.01	$\Omega$
$p_{\text{SCMax}}$	+3750	W
$p_{\text{SCMin}}$	-3750	W
$V_{\text{SCMax}}$	32	V
$V_{\text{SCMin}}$	15	V
$I_{\text{SCRated}}$	150	A

 TABLE III  
 TOTAL ENERGY CONTROL LOOP PARAMETERS

$v_{\text{SCREF}}$	25	V
$C_{\text{SC}}$	100	F
$K_{21}$	0.1	
$p_{\text{FCMax}}$	600	W
$p_{\text{FCMin}}$	0	W
$I_{\text{FCMax}}(\text{Rated})$	46	A
$I_{\text{FCMin}}$	0	A
$\zeta_1$	1	
$\omega_{n1}$	0.4	$\text{rad}\cdot\text{s}^{-1}$

terminated as having the highest power slope of our FC system, where no fuel starvation occurs. It must be noted that, for the small-test bench, the FC maximum power  $p_{\text{FCMax}}$  was set at 600 W; in fact, the rated FC power considered here is 1200 W. Moreover, these two energy control loops, which generated current references  $i_{\text{FCREF}}$  and  $i_{\text{SCREF}}$ , were implemented in the real-time card dSPACE DS1104 using MATLAB-Simulink at a sampling frequency of 25 kHz.

### C. Experimental Results

The experimental tests were carried out by connecting a dc link loaded by a traction motor that was coupled with a small-inertia flywheel and friction load. Fig. 10 presents the waveforms that were obtained during the motor drive cycle, and show the dc-bus voltage, the FC voltage, the load power, the supercapacitor power, the FC power, the supercapacitor current, the FC current, and the supercapacitor voltage [or the supercapacitor state-of-charge (SOC)].

The initial state was in no-load power, and the storage device was fully charged, i.e.,  $v_{\text{SC}} = 25$  V; as a result, both the FC and supercapacitor powers were zero. At  $t = 10$  s, the traction motor speed accelerated to its final speed of 800 r/min; synchronously, the final FC power increased with a limited slope to its limited maximum power of 600 W. Thus, the supercapacitor, which supplies most of the power that is required during motor acceleration, remained in a discharged state after the start of the motor because the steady-state load power (friction load) was greater than the FC-limited maximum power.

Afterward, at  $t = 50$  s, the motor speed decelerated to a stop with a peak load power of about  $-200$  W. The supercapacitor was deeply charged, demonstrating the three phases. First, the

The FC and supercapacitor current regulation loops were realized using analog circuits to function at a high bandwidth. Parameters associated with the dc-bus energy regulation loop and the total energy regulation loop can be seen in Tables II and III, respectively. The FC power dynamic delay is shown in Table III. This value has been experimentally de-

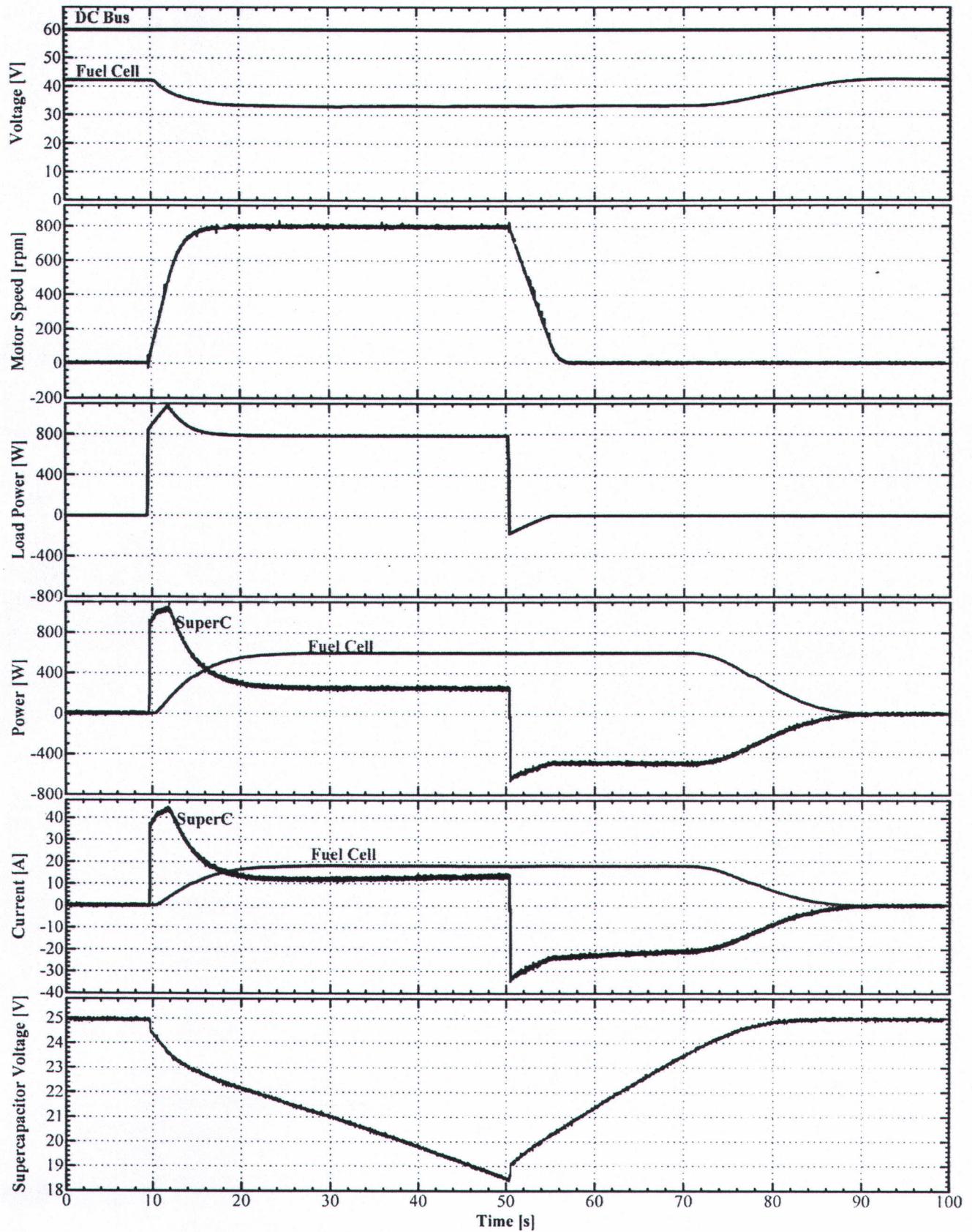


Fig. 10. Hybrid source response during motor drive cycle.

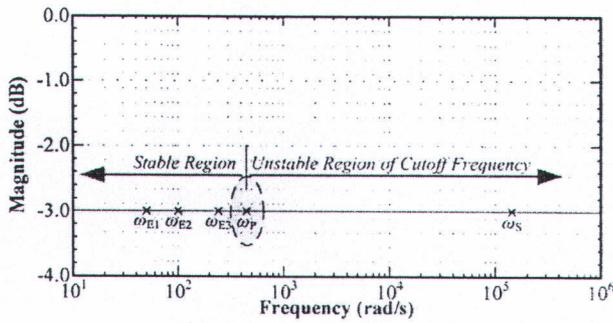


Fig. 11. Setting controllers by choosing the cutoff frequency in frequency space, where  $\omega_S$  is the constant switching frequency of the supercapacitor converter of 25 kHz (157 080  $\text{rad}\cdot\text{s}^{-1}$ ),  $\omega_P$  is the cutoff frequency of the supercapacitor power loop of 450  $\text{rad}\cdot\text{s}^{-1}$ , and  $\omega_E$  is the cutoff frequency of the closed-loop dc-bus energy.

386 supercapacitor recovers the energy that is supplied to the dc bus  
 387 by the FC (600 W) and the traction motor. Second, the superca-  
 388 pacitor is charged only by the FC. Third, the supercapacitor is  
 389 nearly fully charged, which then reduces the charging current.  
 390 After this, both the FC and supercapacitor powers reduce to zero  
 391 when  $v_{SC}$  reaches  $v_{SCREF}$  of 25 V.

392 To demonstrate dynamic regulation of the dc-bus energy  
 393 (voltage) at different nonlinear controller parameters (see  
 394 Fig. 11), the oscilloscope waveforms in Fig. 12 show the dc-  
 395 bus voltage dynamics (representing the flat output  $y_1$ ) to the  
 396 large load power demanded (disturbance) from 0 to 600 W,  
 397 whereas the dc bus was loaded with an electronic load. The  
 398 oscilloscope screens show the dc-bus voltage (the state variable  
 399  $x_1$ , representing the flat output  $y_1$ ), the supercapacitor voltage  
 400 (the state variable  $x_2$ ), the load power, and the supercapacitor  
 401 power (the control input variable  $u_1$ ).

402 The cutoff frequency ( $\omega_P$ ) of the supercapacitor power loop  
 403 was 450  $\text{rad}\cdot\text{s}^{-1}$  (equivalent as a first-order delay with a time  
 404 constant  $T_P$  of 2.2 ms, determined from experimentation). The  
 405 cutoff frequency ( $\omega_E$ ) of the closed-loop dc-bus energy must  
 406 then be lower than the cutoff frequency ( $\omega_P$ ) of the superca-  
 407 pacitor power loop, so that the system is stable.

408 The FC power dynamics were purposely limited (see Fig. 10),  
 409 forcing the supercapacitor to supply the transient load power  
 410 demand. As depicted in Fig. 12(a), the nonlinear controller gains  
 411 used were  $K_{11} = 71 \text{ rad}\cdot\text{s}^{-1}$  and  $K_{12} = 2500 \text{ rad}^2\cdot\text{s}^{-2}$ , so that  
 412 the system damping ratio  $\zeta$  was equal to 0.707 and the natural  
 413 frequency  $\omega_n$  was equal to 50  $\text{rad}\cdot\text{s}^{-1}$ . As a result, the cutoff  
 414 frequency ( $\omega_{E1}$ ) of the closed-loop dc-bus energy was equal to  
 415 50  $\text{rad}\cdot\text{s}^{-1}$ . As depicted in Fig. 12(b), the nonlinear controller  
 416 gains used were  $K_{11} = 141 \text{ rad}\cdot\text{s}^{-1}$  and  $K_{12} = 10\,000 \text{ rad}^2\cdot\text{s}^{-2}$ ,  
 417 so that the system damping ratio  $\zeta$  was equal to 0.707 and the  
 418 natural frequency  $\omega_n$  was equal to 100  $\text{rad}\cdot\text{s}^{-1}$ . As a result,  
 419 the cutoff frequency ( $\omega_{E2}$ ) of the closed-loop dc-bus energy  
 420 was equal to 100  $\text{rad}\cdot\text{s}^{-1}$ . Finally, as depicted in Fig. 12(c),  
 421 the nonlinear controller gains used were  $K_{11} = 354 \text{ rad}\cdot\text{s}^{-1}$   
 422 and  $K_{12} = 62\,500 \text{ rad}^2\cdot\text{s}^{-2}$ , so that the system damping ratio  
 423  $\zeta$  was equal to 0.707 and the natural frequency  $\omega_n$  was equal  
 424 to 250  $\text{rad}\cdot\text{s}^{-1}$ . As a result, the cutoff frequency ( $\omega_{E3}$ ) of the  
 425 closed-loop dc-bus energy was equal to 250  $\text{rad}\cdot\text{s}^{-1}$ . Although

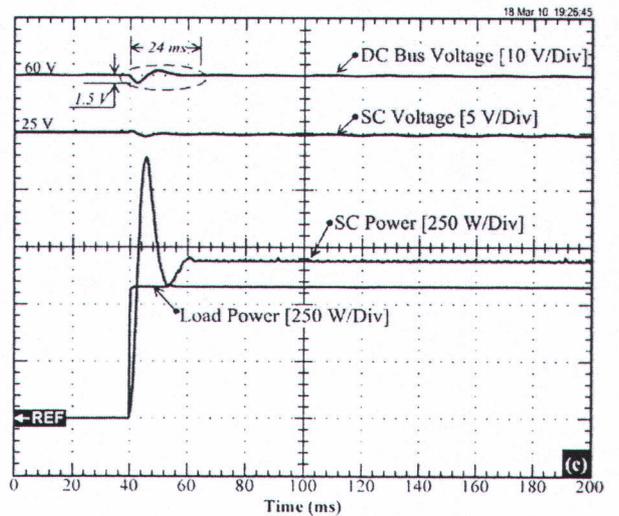
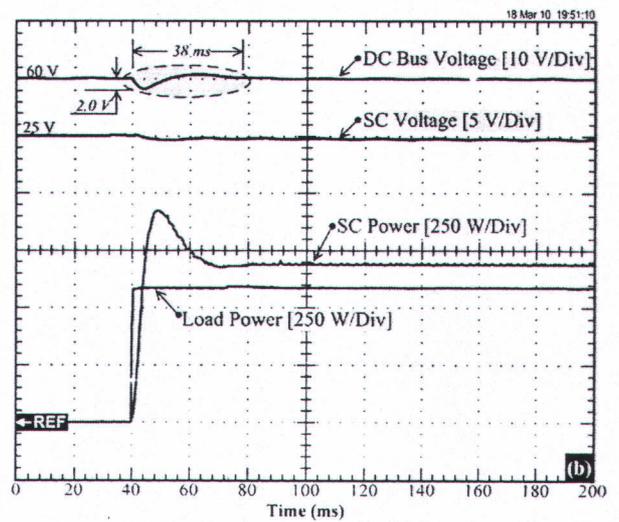
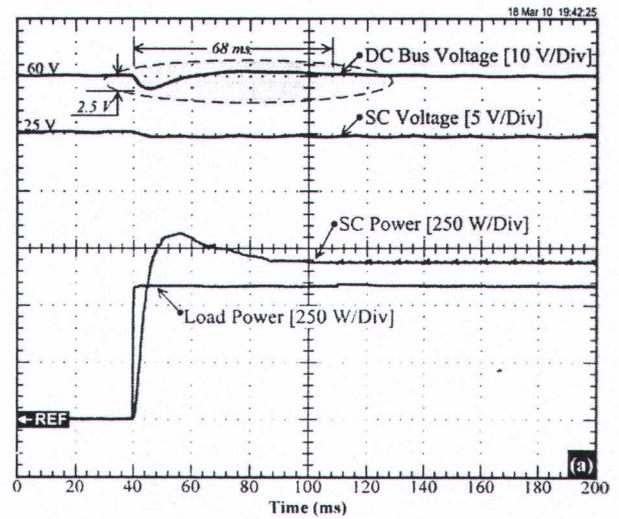


Fig. 12. Comparison of dc-bus voltage regulation (dc-link stabilization) of hybrid power plant during large load step at different controller parameters. (a)  $K_{11} = 71 \text{ rad}\cdot\text{s}^{-1}$  and  $K_{12} = 2500 \text{ rad}^2\cdot\text{s}^{-2}$  ( $\zeta = 0.707$ ;  $\omega_n = 50 \text{ rad}\cdot\text{s}^{-1}$ ). (b)  $K_{11} = 141 \text{ rad}\cdot\text{s}^{-1}$  and  $K_{12} = 10\,000 \text{ rad}^2\cdot\text{s}^{-2}$  ( $\zeta = 0.707$ ;  $\omega_n = 100 \text{ rad}\cdot\text{s}^{-1}$ ). (c)  $K_{11} = 354 \text{ rad}\cdot\text{s}^{-1}$  and  $K_{12} = 62\,500 \text{ rad}^2\cdot\text{s}^{-2}$  ( $\zeta = 0.707$ ;  $\omega_n = 250 \text{ rad}\cdot\text{s}^{-1}$ ).

426 the dynamic response of the control system can be improved  
 427 relative to that shown in the figures by increasing the cutoff  
 428 frequency, this improvement comes at the outflow of reduced  
 429 boundary stability, as illustrated in Fig. 12(c), in which the  
 430 cutoff frequency ( $250 \text{ rad}\cdot\text{s}^{-1}$ ) is closed to  $\omega_P$  ( $450 \text{ rad}\cdot\text{s}^{-1}$ ).  
 431 As presented in Fig. 12(b), the controller parameters at the  
 432 cutoff frequency ( $\omega_{E2}$ ) of  $100 \text{ rad}\cdot\text{s}^{-1}$  ( $\omega_E = \omega_P/4.5$ ) show  
 433 good stability and optimum response (*no oscillation and short*  
 434 *settling time*) of the dc-bus voltage regulation to its desired  
 435 reference of 60 V.

436 Note that there are some losses (static and dynamic losses)  
 437 in the supercapacitor converter (see Figs. 1 and 3), because  
 438 the implemented converters are hard-switching converters, then,  
 439 the power difference between the supercapacitor and the load  
 440 powers (for example, during 100 to 200 ms) can be observed.  
 441 To improve the converter efficiency, soft-switching converters  
 442 may be effective solutions for future work.

443 The flatness-based control is model-based (see the inverse  
 444 dynamics detailed in Figs. 5 and 6). As a result, it may have  
 445 some sensitivity to errors in the model parameters [see (21)  
 446 and (22)]. To substantiate its robustness and dynamic regulation  
 447 of the dc-bus energy (or voltage), the flatness-based control  
 448 was tested with the exact model parameters ( $r_{FC} = 0.14 \Omega$  and  
 449  $r_{SC} = 0.10 \Omega$ ) and for the case of lossless parameters ( $r_{FC} =$   
 450  $0.0 \Omega$  and  $r_{SC} = 0.0 \Omega$ ). Comparisons (robustness) between  
 451 the accurate parameters and the error parameters are given in  
 452 Fig. 13. The oscilloscope generated waveforms obtained during  
 453 the large load step from 0 to around 800 W and showed the dc-  
 454 bus voltage (representing the flat output  $y_1$ ), the supercapacitor  
 455 voltage, the load power (disturbance), the supercapacitor power  
 456 (the control input variable  $u_1$ ). The FC power dynamics were  
 457 intentionally limited (see Fig. 10), forcing the supercapacitor to  
 458 meet the transient load power demand. Similar waveforms are  
 459 seen in Fig. 13(a) and (b).

460 The dc-bus voltage (dc-link stabilization) is minimally influ-  
 461 enced by the large step in load power. Undoubtedly, the perfor-  
 462 mance of the control system is hardly affected by the error con-  
 463 sidered in the model parameters. It is then possible to conclude  
 464 that the nonlinear differential flatness-based approach provides  
 465 an absolutely robust controller in this application.

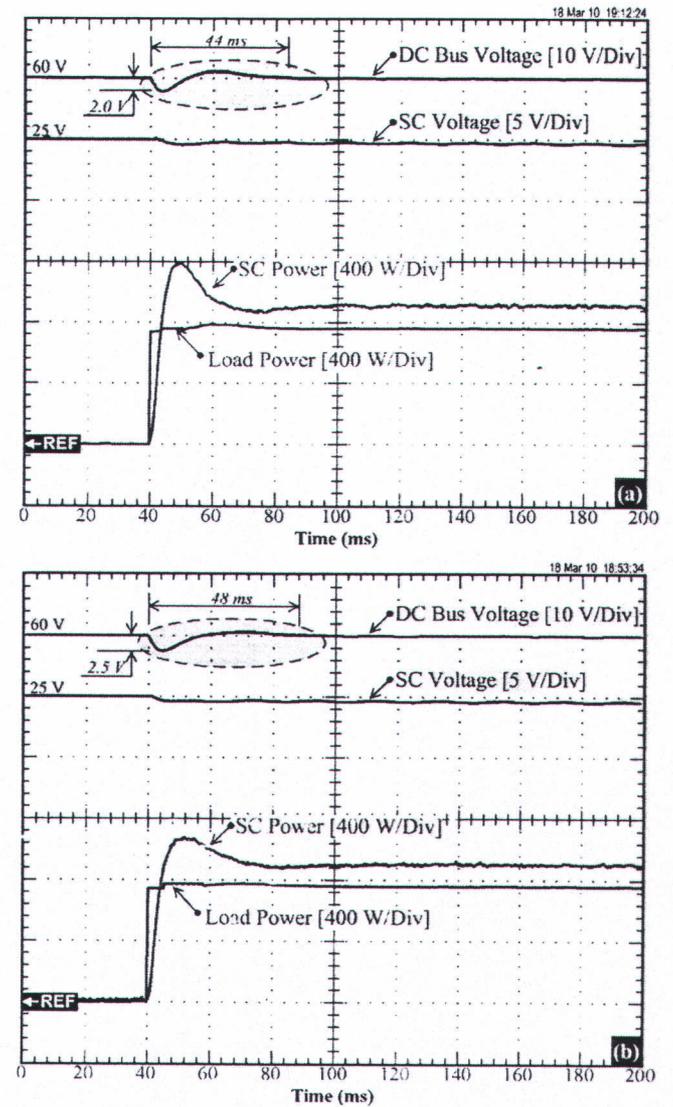
#### 466 D. Performance Comparison Between Nonlinear Control 467 Based on Flatness and Classical Linear Control

468 To compare the performance of the flatness-based control,  
 469 a traditional linear control method presented in [16] was also  
 470 implemented on the hybrid test stand. A dc-bus energy reference  
 471 was represented by  $y_{\text{BusREF}} (=y_{1\text{REF}})$ . A linear feedback PI  
 472 control law is given by the following expression:

$$473 \quad p_{\text{SCREF}} = K_P (y_{\text{BusREF}} - y_{\text{Bus}}) + K_I \int_0^t (y_{\text{BusREF}} - y_{\text{Bus}}) d\tau \quad (31)$$

474 where  $K_P$  and  $K_I$  are the set of controller parameters.

475 Because the supercapacitor current loop is much faster than  
 476 the dc-link voltage loop [so that it can be considered as a pure  
 477 unity gain, see (6)], the open-loop transfer function associated



478 Fig. 13. Comparison of dc-bus voltage regulation (dc-link stabilization) of  
 479 hybrid power plant during large load step. (a) Exact model ( $r_{FC} = 0.14 \Omega$  and  
 480  $r_{SC} = 0.10 \Omega$ ). (b) Error model (robustness) ( $r_{FC} = 0.0 \Omega$  and  $r_{SC} = 0.0 \Omega$ ).

477 with the dc-link voltage regulation can be written as follows:

$$478 \quad \frac{y_{\text{Bus}}(s)}{y_{\text{BusREF}}(s)} = \underbrace{\left( K_P + \frac{K_I}{s} \right)}_{\text{PI-Controller}} \cdot \underbrace{\frac{E_{\text{Bus}}/p_{\text{SC}}}{s}}_{\frac{1}{s}} \cdot \underbrace{\frac{p_{\text{SC}}/p_{\text{SCREF}}}{T_P s + 1}}_{\frac{1}{T_P s + 1}} \quad (32)$$

479 where  $T_P$  is the time constant of an equivalent first-order delay  
 480 of the supercapacitor power regulation loop (or the supercapaci-  
 481 tor current regulation loop). The linear control law of the dc-link  
 482 stabilization detailed earlier is portrayed in Fig. 14; it is similar  
 483 to the nonlinear control law (see Fig. 5), where the PI controller  
 484 also generates a supercapacitor power reference  $p_{\text{SCREF}}$ . The  
 485 main difference between nonlinear control based on the flatness  
 486 property and classical linear control is that the inverse dynamic  
 487 equation, known as the flatness property (see (21) and Fig. 5),  
 appears in the nonlinear control.

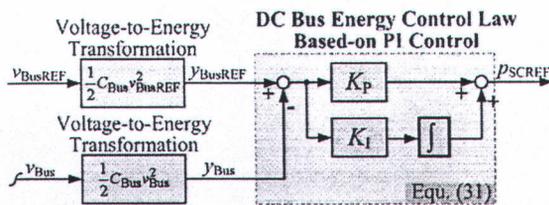


Fig. 14. Control law of the dc-bus energy regulation based on PI control.

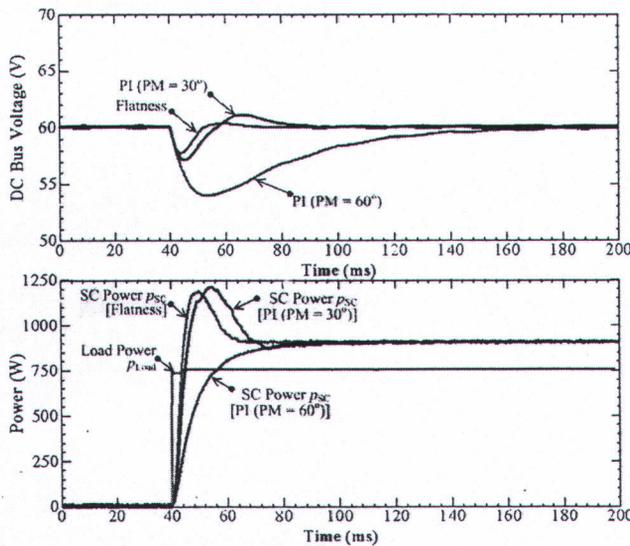


Fig. 15. Comparison of the flatness-based control law with a linear PI control law during a large load step.

Finally, in order to give a reasonable comparison between the methods, the parameters of the linear controller  $K_P$  and  $K_I$  were tuned to obtain the best possible performance. This result was compared to the flatness-based control. In this case,  $K_P = 252 \text{ W}\cdot\text{J}^{-1}$  and  $K_I = 42\,000 \text{ W}\cdot(\text{J}\cdot\text{s})^{-1}$ , so that the desired phase margin was  $30^\circ$ . If  $K_P = 124 \text{ W}\cdot\text{J}^{-1}$  and  $K_I = 3968 \text{ W}\cdot(\text{J}\cdot\text{s})^{-1}$ , the desired phase margin (PM) was  $60^\circ$ . Fig. 15 shows experimental results obtained for both controllers during the large load step. The flatness-based control shows good stability and optimum response of the dc-bus voltage regulation to its desired reference of 60 V. Although dynamic response of the linear control law could be improved relative to that shown in the figures, this enhancement comes at the expense of a reduced stability margin. From these results, we conclude that flatness-based control provides better performance than the classical PI controller.

V. CONCLUSION

A new control approach for a distributed dc generation system supplied by a hybrid source that uses supercapacitors as a fast auxiliary source, in association with a PEMFC as the main source, has been proposed. The reduced-order model of the FC/supercapacitor power plant is flat. A trajectory planning algorithm that allows for energy (voltage) regulation in finite time has also been presented. Theoretically, the flatness-based

control shows better performance than a classical controller (PI or PID controllers) for transitions between equilibrium points, particularly in a nonlinear system.

Experimental results with a small-scale hybrid test bench in the laboratory have authenticated the excellent closed-loop performance of this system. The robustness of the proposed control was demonstrated by test bench results.

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REFERENCES

- [1] M. Hinaje, I. Sadli, J.-P. Martin, P. Thounthong, S. Raël, and B. Davat, "Online humidification diagnosis of a PEMFC using a static DC-DC converter," *Int. J. Hydrogen Energy*, vol. 24, no. 3, pp. 617–625, Sep. 2009.
- [2] R. Toonssen, N. Woudstra, and A. H. M. Verkooijen, "Decentralized generation of electricity from biomass with proton exchange membrane fuel cell," *J. Power Sources*, vol. 194, no. 1, pp. 456–466, Oct. 2009.
- [3] D. Feroldi, M. Serra, and J. Riera, "Design and analysis of fuel-cell hybrid systems oriented to automotive applications," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 4720–4729, Nov. 2009.
- [4] S. S. Williamson and A. Emadi, "Comparative assessment of hybrid electric and fuel cell vehicles based on comprehensive well-to-wheels efficiency analysis," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 856–862, May 2005.
- [5] A. Bergen, L. Pitt, A. Rowe, P. Wild, and N. Djilali, "Experimental assessment of a residential scale renewable-regenerative energy system," *J. Power Sources*, vol. 186, no. 1, pp. 158–166, Jan. 2009.
- [6] S. Biset, L. Nieto Deglioumini, M. Basualdo, V. M. Garcia, and M. Serra, "Analysis of the control structures for an integrated ethanol processor for proton exchange membrane fuel cell systems," *J. Power Sources*, vol. 192, no. 1, pp. 107–113, Jul. 2009.
- [7] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel starvation: Analysis of a PEM fuel cell system," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 52–59, Jul./Aug. 2009.
- [8] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat, and M. Hinaje, "Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3892–3904, Oct. 2009.
- [9] J. Bernard, S. Delprat, F. N. Büchi, and T. M. Guerra, "Fuel-cell hybrid powertrain: Toward minimization of hydrogen consumption," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3168–3176, Sep. 2009.
- [10] A. E. Auld, J. Brouwer, K. Ma Smedley, and S. Samuelsen, "Load-following strategies for evolution of solid oxide fuel cells into model citizens of the grid," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 617–625, Sep. 2009.
- [11] E. H. El Brouji, O. Briat, J. M. Vinassa, N. Bertrand, and E. Woïrgard, "Impact of calendar life and cycling ageing on supercapacitor performance," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3917–3929, Oct. 2009.
- [12] P. Thounthong, S. Raël, and B. Davat, "Analysis of supercapacitor as second source based on fuel cell power generation," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 247–255, Mar. 2009.
- [13] T. Kojima, T. Ishizu, T. Horiba, and M. Yoshikawa, "Development of lithium-ion battery for fuel cell hybrid electric vehicle application," *J. Power Sources*, vol. 189, no. 1, pp. 859–863, Apr. 2009.
- [14] P. Thounthong, S. Raël, and B. Davat, "Control algorithm of fuel cell and batteries for distributed generation system," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 148–155, Jan. 2008.
- [15] M. Uzunoglu and M. S. Alam, "Modeling and analysis of an FC/UC hybrid vehicular power system using a novel-wavelet-based load sharing algorithm," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 263–272, Mar. 2008.
- [16] P. Thounthong, S. Raël, and B. Davat, "Control strategy of fuel cell and supercapacitors association for distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3225–3233, Dec. 2007.



- 579 [17] E. Schaltz, A. Khaligh, and P. O. Rasmussen, "Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3882–3891, Oct. 2009.
- 580 [18] P. Thounthong, S. Raël, and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," *J. Power Sources*, vol. 193, no. 1, pp. 376–385, Aug. 2009.
- 581 [19] P. Thounthong and S. Raël, "The benefits of hybridization," *IEEE Ind. Electron. Mag.*, vol. 3, no. 3, pp. 25–37, Sep. 2009.
- 582 [20] A. Payman, S. Pierfederici, and F. Meibody-Tabar, "Energy control of supercapacitor/fuel cell hybrid power source," *Energy Convers. Manage.*, vol. 49, no. 6, pp. 1637–1644, Jun. 2008.
- 583 [21] M. Fliess, J. Lévine, Ph. Martin, and P. Rouchon, "Flatness and defect of nonlinear systems: Introductory theory and examples," *Int. J. Contr.*, vol. 61, no. 6, pp. 1327–1361, 1995.
- 584 [22] H. Aschemann and D. Schindele, "Sliding-mode control of a high-speed linear axis driven by pneumatic muscle actuators," *IEEE Trans. Ind. Electron.*, vol. 55, no. 11, pp. 3855–3864, Nov. 2008.
- 585 [23] M. A. Danzer, J. Wilhelm, H. Aschemann, and E. P. Hofer, "Model-based control of cathode pressure and oxygen excess ratio of a PEM fuel cell system," *J. Power Sources*, vol. 176, no. 2, pp. 515–522, 2008.
- 586 [24] P. S. P. da Silva and P. Rouchon, "Flatness-based control of a single qubit gate," *IEEE Trans. Automat. Contr.*, vol. 53, no. 3, pp. 775–779, Apr. 2008.
- 587 [25] E. Song, A. F. Lynch, and V. Dinavahi, "Experimental validation of nonlinear control for a voltage source converter," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 5, pp. 1135–1144, Sep. 2009.
- 588 [26] T. Rabbani, S. Munier, D. Dorchie, P. Malaterre, A. Bayen, and X. Litrico, "Flatness-based control of open-channel flow in an irrigation canal using scada," *IEEE Control Syst. Mag.*, vol. 29, no. 5, pp. 22–30, Oct. 2009.
- 589 [27] A. Gensior, H. Sira-Ramírez, J. Rudolph, and H. Güldner, "On some nonlinear current controllers for three-phase boost rectifiers," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 360–370, Feb. 2009.
- 590 [28] V. Morio, F. Cazaurang, and Ph. Vernis, "Flatness-based hypersonic reentry guidance of a lifting-body vehicle," *Control Eng. Practice*, vol. 17, no. 5, pp. 588–596, May 2009.
- 591 [29] S. K. Agrawal, K. Pathak, J. Franch, R. Lampariello, and G. Hirzinger, "A differentially flat open chain space robot with arbitrarily oriented joint axes and two momentum wheels at the base," *IEEE Trans. Automat. Contr.*, vol. 54, no. 9, pp. 2185–2191, Sep. 2009.
- 592 [30] K. Rajashekar, J. Grieve, and D. Dagggett, "Hybrid fuel cell power in aircraft," *IEEE Ind. Appl. Mag.*, vol. 14, no. 4, pp. 54–60, Jul./Aug. 2008.
- 593 [31] S. Y. Choe, J. W. Ahn, J. G. Lee, and S. H. Baek, "Dynamic simulator for a PEM fuel cell system with a PWM DC/DC converter," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 669–680, Jun. 2008.
- 594 [32] S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura, "Integration of an energy capacitor system with a variable-speed wind generator," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 740–749, Sep. 2009.
- 595 [33] P. Thounthong, B. Davat, S. Raël, and P. Sethakul, "Fuel cell high-power applications," *IEEE Ind. Electron. Mag.*, vol. 3, no. 1, pp. 32–46, Mar. 2009.
- 596 [34] M. H. Todorovic, L. Palma, and P. N. Enjeti, "Design of a wide input range DC–DC converter with a robust power control scheme suitable for fuel cell power conversion," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1247–1255, Mar. 2008.
- 597 [35] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and C. H. Kim, "A coordinated control method for leveling PV output power fluctuations of PV–diesel hybrid systems connected to isolated power utility," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 153–162, Mar. 2009.
- 598 [36] W. Hu, Z. Chen, Y. Wang, and Z. Wang, "Flicker mitigation by active power control of variable-speed wind turbines with full-scale back-to-back power converters," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 640–649, Sep. 2009.
- 599 [37] S. D. Sudhoff, K. A. Corzine, S. F. Glover, H. J. Hegner, and H. N. Robey, Jr., "DC link stabilized field oriented control of electric propulsion systems," *IEEE Trans. Energy Convers.*, vol. 13, no. 1, pp. 27–33, Mar. 1998.
- 600 [38] D. Feroldi, M. Serra, and J. Riera, "Energy management strategies based on efficiency map for fuel cell hybrid vehicles," *J. Power Sources*, vol. 190, no. 2, pp. 387–401, May 2009.
- 601 [39] Z. Jiang, L. Gao, and R. A. Dougal, "Adaptive control strategy for active power sharing in hybrid fuel cell/battery power sources," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 507–515, Jun. 2007.
- 602 [40] C. Y. Li and G. P. Liu, "Optimal fuzzy power control and management of fuel cell/battery hybrid vehicles," *J. Power Sources*, vol. 192, no. 2, pp. 525–533, Jul. 2009.
- 603 [41] M. Fliess, J. Lévine, Ph. Martin, and P. Rouchon, "A lie–bäcklund approach to equivalence and flatness of nonlinear systems," *IEEE Trans. Automat. Contr.*, vol. 44, no. 5, pp. 922–937, May 1999.
- 604 [42] G. Millérioux and J. Daafouz, "Flatness of switched linear discrete-time systems," *IEEE Trans. Automat. Contr.*, vol. 54, no. 3, pp. 615–619, Mar. 2009.
- 605 [43] C. P. Mudannayake and M. F. Rahman, "Control design for an induction machine based 42 V integrated starter alternator," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 14–25, Jul./Aug. 2009.



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